UNIVERSIDAD DE CÓRDOBA

# TESIS DOCTORAL

# ESTUDIO DE DURABILIDAD Y DE COMPORTAMIENTO MECÁNICO EN HORMIGONES Y MATERIALES TRATADOS CON CEMENTO, APLICANDO RESIDUOS INDUSTRIALES Y ÁRIDOS RECICLADOS


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Córdoba, 2017

TITULO: *Estudio de durabilidad y de comportamiento mecánico en hormigones y materiales tratados con cemento, aplicando residuos industriales y áridos reciclados*

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**TÍTULO DE LA TESIS:** ESTUDIO DE DURABILIDAD Y DE COMPORTAMIENTO MECÁNICO EN HORMIGONES Y MATERIALES TRATADOS CON CEMENTO, APLICADO RESIDUOS INDUSTRIALES Y ÁRIDOS RECICLADOS.

**DOCTORANDO:** Manuel García Beltrán

**INFORME RAZONADO DE LOS DIRECTORES DE LA TESIS**

En las últimas décadas, el constante incremento de demanda energética por parte de la humanidad ha llevado al sector de la energía a la búsqueda y desarrollo de nuevos procedimientos de generación de energía que permita satisfacer dicha demanda.

Un método de obtención de energía en auge en España, y más en concreto en Andalucía, es el de la ***combustión de biomasa*** procedente del sector agroindustrial a partir de restos de poda de olivo, chopo, etc. Sin embargo, la combustión de este tipo de materiales genera residuos con difícil salida medioambiental (***cenizas de fondo de biomasa***), ya que son depositados en vertederos perjudicando con ello el entorno natural.

Por este motivo, gracias al fomento de la sensibilidad medioambiental en los últimos años se están realizando esfuerzos para ofrecer otra salida a este tipo de residuos. Por otro lado, el desarrollo y evolución de la tecnología asociada al sector de la ingeniería se ha realizado poniendo un especial énfasis en el medio ambiente mediante la búsqueda de técnicas y procesos que favorezcan la reducción de uso de recursos naturales y a su vez, permita minimizar el impacto ambiental.

En el caso del sector de la ingeniería de la construcción, la generación de ***Residuos de Construcción y Demolición*** **(RCD)** ha aumentado significativamente gracias a la demolición de construcciones, lo que ha conducido al agravamiento del estado del entorno natural por la deposición de estos residuos en vertedero. En Andalucía, el fomento de leyes y normativas en favor del medio ambiente han impulsado la investigación, optimización y aplicación de este tipo de residuos para ser devueltos de nuevo al proceso constructivo.

Sin embargo, para que residuos procedentes del sector energético, como las cenizas de biomasa, y/o residuos procedentes del sector de la construcción, como residuos de construcción y demolición puedan ser reciclados y reutilizados, deben haberse realizado previamente estudios de investigación que permitan conocer sus propiedades y su comportamiento al ser aplicados.

Por ello, esta Tesis Doctoral está sujeta al concepto de "***Construcción Sostenible***", y bajo este concepto el desarrollo de la misma ha estado enfocado a tres aspectos fundamentales: reutilización de recursos, viabilidad técnica y sostenibilidad medioambiental.

Bajo estos tres pilares, la presente Tesis Doctoral está enfatizada en el estudio de la viabilidad técnica de cenizas de fondo de biomasa mediante el análisis de propiedades mecánicas y de durabilidad en hormigones fabricados con residuos de construcción y demolición. Mediante este estudio se pretende poner de nuevo en servicio dos tipos residuos de forma conjunta, reduciendo por partida doble dos problemas medioambientales.

El trabajo de investigación realizado ha dado como fruto la publicación de cuatro artículos en revistas de reconocido prestigio a nivel mundial en el sector de la ingeniería civil y del medio ambiente, siendo tres de ellas de primer cuartil y una de cuarto cuartil:

1. Beltrán, M.G., Barbudo, A., Agrela, F., Jiménez, J.R., De Brito, J., (2016). *Mechanical performance of bedding mortars made with olive biomass bottom ash.* Construction and Building Materials 112, 699-707.
2. Beltrán, M.G., Barbudo, A., Agrela, F., Galvín, A.P., Jiménez, J.R. (2014). *Effect of cement addition on the properties of recycled concretes to reach control concretes strengths.* Journal of Cleaner Production 79,124-133.
3. Beltrán, M.G., Agrela, F., Barbudo, A., Ayuso, J., Ramírez, A., (2014). *Mechanical and durability properties of concretes manufactured with biomass bottom ash and recycled coarse aggregates.* Construction and Building Materials 72, 231-238.
4. Agrela, F., Beltrán, M.G., Cabrera, M., López, M., Rosales, J., Ayuso, J., (2017). *Properties of recycled concrete manufacturing with all-in recycled aggregates and processed biomass bottom ash.* Waste and Biomass Valorization. DOI 10.1007/s12649-017-9880-6.

A su vez, se adjunta una aportación en un artículo de una revista técnica indexada, una aportación a un Congreso y una aportación a una revista técnica no indexada. Por tanto, la presente Tesis Doctoral cumple de forma rigurosa todos los objetivos establecidos previamente respecto al estudio de la aplicación de cenizas de fondo de biomasa en hormigones, así como al análisis de las propiedades mecánicas y de durabilidad de hormigones fabricados con áridos reciclados junto con cenizas de fondo de biomasa.

Por ello, se autoriza la presentación de la Tesis Doctoral "Estudio de durabilidad y de comportamiento mecánico en hormigones y materiales tratados con cemento, aplicando residuos industriales y áridos reciclados".

Córdoba, 6 de abril de 2017

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*A Inma Ruiz, mi prometida*

*mi compañera,*

*mi vida entera…*

# AGRADECIMIENTOS

En primer lugar, me gustaría mostrar mis más sinceros agradecimientos a mis padres, Manuel y Antonia, y a mi hermana, Mariangeles, a quien les debo todo lo que soy y todo lo que he conseguido, ya que su amor, esfuerzo y dedicación han sido esenciales en cada momento de mi vida.

En segundo lugar, me gustaría agradecer a Inma Ruiz, mi prometida, todos sus consejos, esfuerzos e inestimable ayuda para la redacción de esta Tesis Doctoral.

No podría estar sino infinitamente agradecido a mis directores de doctorado, los Dres. Francisco Agrela Sainz, y Mª Auxiliadora Barbudo Muñoz por confiar siempre en mí, por los conocimientos que me han aportado todos estos años y por su constante ayuda y dedicación en cada momento que he lo necesitado.

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# RESUMEN

En la actualidad, la elevada demanda de energía y productos de consumo a nivel mundial induce a que numerosas industrias produzcan bienes y servicios que tienen como resultado la generación de residuos con difícil o nula salida técnica y medioambiental. Entre estas industrias se encuentra la industria productora de energía a partir de biomasa. Este tipo de industrias generan dos tipos de residuos: ***cenizas volantes de biomasa*** que son extraídas por corriente de gases, y ***cenizas de fondo de biomasa***, que son extraídas desde el fondo de la cámara de combustión.

Otras industrias, como la construcción, generan ***residuos de construcción y demolición*** que, comúnmente, tienen como punto de destino su deposición en vertederos. Ello conlleva un acortamiento de la vida útil de éstos, y como consecuencia, un mayor impacto ambiental.

Ante esta situación, la presente Tesis Doctoral pretende ampliar el conocimiento existente sobre la valorización y reutilización de estos residuos (cenizas de fondo de biomasa y áridos reciclados procedentes de RCD) en el sector de la construcción.

Con ese fin, la línea de investigación seguida ha sido fundada sobre dos pilares esenciales: el primero, el análisis de la capacidad cementante de las cenizas de fondo de biomasa y como sustituto de la fracción fina en la fabricación de hormigones, y el segundo, la posibilidad de utilizar un árido reciclado de granulometría continua reemplazando a los áridos naturales, tanto en su fracción fina como en la gruesa, en su aplicación como hormigones no estructurales.

Para ello, se analizaron las propiedades mecánicas y de durabilidad de hormigones fabricados con áridos reciclados y/o cenizas de fondo de biomasa, cuyas magnitudes fueron comparadas ampliamente con estudios previos de otros autores.

De los resultados obtenidos y su análisis puede concluirse que la incorporación de cenizas de fondo de biomasa junto con áridos reciclados reduce las propiedades mecánicas y de durabilidad del hormigón. Sin embargo, se demuestra la posibilidad de aplicar cenizas de fondo de biomasa y áridos reciclados, siempre bajo tasas de incorporación reducidas y para hormigones no estructurales con exigencias técnicas reducidas.

El conocimiento es la principal baza para que residuos procedentes de diversas industrias puedan ser reciclados y reutilizados en el sistema de producción en la construcción. Concretamente, la conjunción de los materiales anteriormente mencionados en la fabricación de hormigones, concede a esta investigación un carácter exclusivo e innovador.

Así pues, la principal motivación de esta Tesis Doctoral ha sido la de ampliar el conocimiento existente hasta la fecha para contribuir al fomento del reciclaje de materiales en el sector de la construcción, una acción vital y fundamental para el desarrollo de la humanidad y para la vida del planeta.

# ABSTRACT

Today, the high demand for energy and consumer products worldwide leads industries to produce goods and services that result in the generation of waste with a difficult technical and environmental solution. One of these industries is the energy-producing industry from biomass.

This type of industry generates two types of waste: fly ash from biomass that is extracted by gas stream, and biomass bottom ash, which is extracted from the bottom of the combustion chamber.

Other industries, such as construction, generate construction and demolition waste (CDW), which commonly have their disposal in landfills. This implies a shortening of their useful life, and consequently, a greater environmental impact.

In this situation, this Doctoral Thesis aims to extend the existing knowledge about the recovery and reuse of this waste (biomass bottom ash and recycled aggregates from CDW) in the construction sector.

Thus, the line of investigation followed is based on two essential parts: the first one, the analysis of the cementing capacity of biomass bottom ash and as a substitute for the fine fraction in the manufacture of concrete, and the second, the possibility of using a recycled aggregate of continuous granulometry replacing the natural aggregates, both in their fine fraction as in the coarse one, in its application as non-structural concretes.

To do this, the mechanical and durability properties of concrete made from recycled aggregates and/or biomass bottom ash were analyzed, whose magnitudes were compared with previous studies from other authors.

From the results obtained and their analysis it can be concluded that the incorporation of biomass bottom ash together with recycled aggregates reduces

the mechanical and durability properties of the concrete. However, the possibility of applying biomass bottom ash and recycled aggregates is demonstrated at low incorporation rates and for non-structural concretes with reduced technical requirements.

Knowledge is the main asset so that waste from various industries can be recycled and reused to the construction production system. Specifically, the combination of above materials, applied in concrete gives this research an exclusive and innovative character.

So, the main motivation of this Doctoral Thesis has been to expand existing knowledge to contribute to the promotion of recycling, a vital and fundamental action for the development of humanity and for the life of the World.

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# ACRÓNIMOS

**CNUMAD:** Conferencia de las Naciones Unidades sobre Medio Ambiente y Desarrollo.

**CEDEX:** Centro de Estudios y Experimentación de Obras Públicas

**RCD:** Residuos de Construcción y Demolición

**AR:** Árido reciclados

**ARH:** Árido reciclado de hormigón

**ARM:** Árido reciclado mixto

**RI:** Residuos industriales

**PERMAR:** Plan Estatal Marco de Gestión de Residuos

**CNAE:** Clasificación Nacional de Actividades Económicas

**CVB:** Cenizas volantes de biomasa

**CFB:** Cenizas de fondo de biomasa

**AN:** Arena natural

**UPV:** Velocidad de impulsos ultrasónicos

# CAPÍTULO I

## *INTRODUCCIÓN*

# CAPÍTULO I

## *INTRODUCCIÓN*

La Tesis Doctoral que aquí se presenta, con título "Estudio de durabilidad y de comportamiento mecánico en hormigones y materiales tratados con cemento aplicando residuos industriales y áridos reciclados, dirigida por los doctores Francisco Agrela Sainz y Mª Auxiliadora Barbudo Muñoz, y llevada a cabo en el Departamento de Ingeniería Rural de la Universidad de Córdoba, ha pretendido ampliar el espectro de conocimientos respecto al uso de diferentes tipos de materiales reciclados y residuos industriales en la fabricación de hormigones.

Para ello, diferentes fases han sido llevadas a cabo, desde el estudio de capacidad cementante de cenizas de fondo de biomasa hasta la aplicación de las mismas junto con materiales reciclados "todo-uno" en hormigones, pasando por el análisis de propiedades mecánicas y de durabilidad de hormigones con áridos reciclados.

Los frutos de las diferentes investigaciones han dado como resultado varias publicaciones en revistas científicas y congresos, y cuya recopilación queda depositada en el presente trabajo.

## 1.1 SOSTENIBILIDAD

*Está en manos de la humanidad hacer que el desarrollo sea sostenible, duradero, o sea, asegurar que satisfaga las necesidades del presente, sin comprometer la capacidad de las futuras generaciones para satisfacer las propias. El concepto de desarrollo duradero implica límites - no límites absolutos, sino limitaciones que imponen a los recursos del medio ambiente el estado actual de la tecnología y de la organización social, y la capacidad de la biosfera de absorber los efectos de las actividades humanas. Pero tanto la tecnología como la organización social pueden ser ordenadas y mejoradas de manera que abran el camino a una nueva era de crecimiento económico.* (Organización de las Naciones Unidas, 1987).

Este principio de Sostenibilidad se formalizó por primera vez en el Informe Brundtland de 1987, producto de la Asamblea de las Naciones Unidas, que se realizó el 20 de marzo del mismo año.

Dicha asamblea fue dirigida por la ex Ministra de Noruega, la Dra. Gro Harlem Brundtland, cuyo propósito fue analizar, criticar y replantear las políticas de desarrollo económico globalizador, reconociendo que el actual avance social se está llevando a cabo a un costo medioambiental alto.

El concepto de Sostenibilidad está directamente asociado a la acción del hombre en relación a su entorno. Implica la necesidad de equilibrio entre el hombre y los factores o recursos que tiene para hacer posible el funcionamiento de todas sus partes.

En junio de 1992 se llevó a cabo la Conferencia de las Naciones Unidas Sobre Medio Ambiente y Desarrollo – *CNUMAD*, en Río de Janeiro, Brasil. En el evento organizado por las Naciones Unidas, y mejor conocido como "La Cumbre de la

Tierra", se realizó la «Declaración de Río sobre el Medio Ambiente y el Desarrollo», la cual consolida el concepto de desarrollo sostenible.

A partir de aquel entonces comenzó a promoverse el concepto de desarrollo sostenible a nivel mundial, influyendo en la planificación y gestión del sector productivo, para garantizar el mejor aprovechamiento de los recursos y disminuir significativamente el impacto sobre el Medio Ambiente.

Además, para fortalecer el compromiso en la población y garantizar que el concepto de sostenibilidad sea considerado en todos los factores involucrados en la relación entre el hombre y su entorno, se ha incluido como principio, de obligatorio cumplimiento, en el marco legislativo de muchos países. Esto quiere decir que el desarrollo sostenible no es solo un derecho sino también un deber de todos los ciudadanos.

## 1.2. CONSTRUCCIÓN SOSTENIBLE

Sistema de construcción civil que busca enfrentar y proponer soluciones a los principales problemas ambientales de nuestra época, de forma tal de atender las necesidades de habitación y uso de espacios del hombre moderno, preservando el medioambiente y los recursos naturales, y garantizando calidad de vida para las generaciones actuales y futuras. La Construcción Sostenible lleva asociada tres verbos: **reducir, conservar y mantener**.

La *reducción* en la utilización de los recursos disponibles a través de la reutilización, el reciclaje, la utilización de recursos renovables y un uso eficiente de los recursos. Se tratará de aumentar la vida útil de los productos y la eficiencia energética, así como dar uso multifuncional del terreno.

La *conservación* de las áreas naturales y de la biodiversidad a partir de la restricción en la utilización del terreno, una reducción de la fragmentación y la prevención de las emisiones tóxicas.

El *mantenimiento* de un ambiente interior saludable y de la calidad de los ambientes urbanizados a través de la utilización de materiales con bajas emisiones tóxicas, una ventilación efectiva, una compatibilidad con las necesidades de los ocupantes, previsiones de transporte, seguridad y disminución de ruidos, contaminación y olores.

Actualmente, muchos países están desarrollando construcciones innovadoras con cubiertas vegetales, las cuales disminuyen el consumo energético de la edificación, además de favorecer la envolvente térmica de la misma.

La Agenda 2030 para el Desarrollo Sostenible de la Organización de Naciones Unidas, establece varios objetivos que están vinculados específicamente con la Construcción Sostenible:

**Objetivo 7:** *Garantizar el acceso a una energía asequible, segura, sostenible y moderna para todos.*

Para 2030, ampliar la infraestructura y mejorar la tecnología para así duplicar la tasa mundial de eficiencia energética en todos los países en desarrollo, en particular los países menos adelantados, los pequeños Estados insulares en desarrollo y los países en desarrollo sin litoral, en consonancia con sus respectivos programas de apoyo.

**Objetivo 9:** *Construir infraestructuras resilientes, promover la industrialización inclusiva y sostenible y fomentar la innovación.*

Para 2030, mejorar la infraestructura y reajustar las industrias para que sean sostenibles, usando los recursos con mayor eficacia y promoviendo la adopción de tecnologías y procesos industriales limpios y ambientalmente racionales, y logrando que todos los países adopten medidas de acuerdo con sus capacidades respectivas.

**Objetivo 11:** *Lograr que las ciudades y los asentamientos humanos sean inclusivos, seguros, resilientes y sostenibles.*

Proporcionar apoyo a los países menos adelantados, incluso mediante la asistencia financiera y técnica, para que puedan construir edificios sostenibles y resilientes utilizando materiales locales.

Un aspecto fundamental de las construcciones sostenibles es el proceso de fabricación de los materiales de construcción, así como de los productos de los cuales muchos están formados, ya que este proceso por lo general ocasiona un impacto ambiental.

Este impacto tiene su origen en la extracción de los recursos naturales necesarios para su elaboración, incluyendo el proceso de fabricación y el consumo de energía, que deriva en emisiones tóxicas a la atmósfera.

Los principales efectos sobre el Medio Ambiente de los materiales utilizados en la construcción son los siguientes: consumo energético; producción de residuos sólidos; incidencia en el efecto invernadero; incidencia en la capa de ozono; otros factores de contaminación ambiental.

Es por ello, que surge la necesidad de realizar evaluaciones técnicas de los materiales de construcción, con dos propósitos principales:

1. Evitar el uso de materiales que puedan deteriorar el Medio Ambiente a corto o largo plazo.
2. Obtener el mejor aprovechamiento de los materiales a través de su optimización y reutilización.

Bajo estas dos premisas debe favorecerse el reciclaje de materiales primarios cuyo destino final en el pasado era su deposición en vertedero, conllevando problemas medioambientales derivados de contaminación del medio natural y lixiviación de elementos peligrosos. Cualquier sociedad que tenga entre sus objetivos políticas de responsabilidad medioambiental óptimas debe ser capaz de dar una salida medioambiental al mayor número de productos susceptibles de ser reutilizados.

Así, en el proceso de reciclaje han de ser tenidos en cuenta varios factores clave a la hora de determinar el rendimiento o grado de aprovechamiento del producto a reciclar. Entre estos factores se encuentran la viabilidad económica del proceso, mejoras medioambientales, reciclaje, toxicidad derivadas del propio reciclado del material, porcentaje de del producto, calidad del producto final reciclado y posibles usos del producto a reciclar.

Existe una elevada experiencia en el reciclaje de productos de consumo doméstico y en la determinación de los factores que intervienen en el proceso. Según la Agencia Europea de Estadística (Eurostat), en España se trataron 108.475.000 Toneladas de residuos, de las cuales, 48.745.000 Toneladas fueron recicladas, correspondiendo un 44,93% del total, mientras que la media de residuos reciclados en la zona Euro fue de 36,43%.

Respecto a la clase del residuo, no sólo debe ser tenido en cuenta el residuo procedente de esta clase de consumo, sino un espectro más amplio abarcando residuos derivados de la fabricación de productos de consumo, residuos industriales, residuos derivados de procesos de construcción y deconstrucción o residuos derivados de la generación de electricidad entre otros.

Sin embargo, no es posible dar una salida medioambiental a productos susceptibles de ser reciclados si no existen fundamentos sólidos que apoyen su uso. Por ello, la investigación se torna fundamental para conseguir tal fin, en primer lugar, para conocer su naturaleza como material procesado, y, en segundo lugar, para conocer sus posibilidades de reutilización.

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# CAPÍTULO II

## *RESIDUOS TRATADOS PARA SU APLICACIÓN EN HORMIGONES*

# CAPÍTULO II

## *RESIDUOS TRATADOS PARA SU APLICACIÓN EN HORMIGONES*

Se expone en este capítulo el estado del arte concerniente a los residuos tratados que han sido analizados y aplicados en hormigones, desde los residuos de construcción y demolición hasta residuos procedentes de procesos industriales, tanto de carácter biológico como mineral.

### 2.1. RESIDUOS DE CONSTRUCCIÓN Y DEMOLICIÓN

#### *Concepto*

Se define el **Residuo de Construcción y Demolición** (RCD) como "*cualquier sustancia u objeto que, cumpliendo con la definición de residuo incluida en el artículo 3.A de la ley 10/1998 de 21 de abril, se genera en una obra de excavación, nueva construcción, reparación, remodelación, rehabilitación y demolición, incluyendo el de obra menor y reparación domiciliaria*" (Real Decreto 105/2008). Este tipo de residuos está constituido principalmente por hormigón, partículas cerámicas, áridos naturales, yesos, maderas, metales, vidrios y otro tipo desechos derivados del proceso de demolición y de construcción.

Históricamente, en España la salida de este tipo residuos era su deposición en vertederos o escombreras sin ningún tipo de control medioambiental. Este hecho generaba evidentes problemas de contaminación de la naturaleza.

Actualmente existen diversos elementos de control que permiten gestionar este tipo de residuos de una manera más eficiente e inocua para el medioambiente. Sin embargo, a pesar de la optimización de la gestión de los RCD, su producción se ha reducido considerablemente debido a la recesión económica experimentada en la Unión Europea, máxime en España debido a la caída del sector de la construcción, lo que propiciado a su vez un descenso en las demoliciones de edificios existentes.

El porcentaje de reciclado de RCD en España es muy reducido en comparación con otros países de la zona Euro, donde países como Dinamarca, Holanda, Estonia o Alemania reciclan más del 85% (European Commision DG ENV, 2011). Para mejorar el porcentaje de reciclado se han realizado varios planes nacionales de los cuales dos están vigentes (II Plan Nacional de Residuos 2008-2015 y Programa Estatal de Prevención de Residuos 2015-2020).

Se torna por tanto necesario promover medidas que incentiven la reutilización de este tipo de residuos en diferentes ámbitos, con el fin de reducir la explotación de recursos naturales existentes y con la necesidad de reducir la cantidad de residuos depositados en vertederos que perjudican necesariamente el medio ambiente.

### *Composición de los RCD*

Los RCD se componen principalmente de materiales de naturaleza pétrea, en porcentajes que varían entre el 75% y 95% en la mayoría de los casos (**Figura 2.1**). Dicha fracción pétrea constituye la base del material para la producción de áridos reciclados y se puede subdividir en diferentes materiales usados en la construcción (ladrillos y materiales cerámicos, hormigón, áridos naturales y asfalto). El resto de materiales reciclados o recuperados con valor (madera, metales, etc.) tienen su propia dinámica de mercado.

La mayor parte de los residuos que se generan en actividades de construcción y demolición, no suelen revestir características de peligrosidad, pero hay que tener en cuenta que su recogida de forma no selectiva puede provocar la contaminación de los residuos en su conjunto, lo que impide someterlos a un aprovechamiento apropiado.

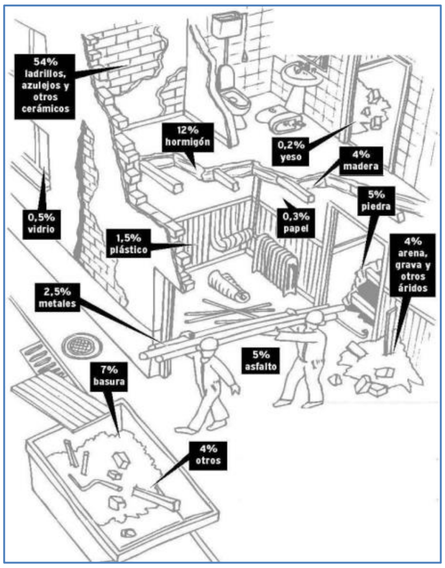


**Figura 2.1.** Componentes de los Residuos de Construcción y Demolición

Fuente: Observatorio de la Construcción (2008)

## *Procesado y transformación*

El RCD requiere un procesado que permita a éste tener las propiedades adecuadas para su reutilización. En su origen, el RCD forma parte de una edificación existente la cual es deconstruida y demolida. Es importante remarcar el término "*demolición selectiva en origen*" (Sánchez de Juan, 2004), por el cual se procede a la discriminación de ciertos materiales indeseables para la fase ulterior (yesos, escayolas, maderas, metales). El proceso de demolición da lugar a un producto de gran tamaño denominado "escombro", el cual está compuesto de diferentes mariales (hormigón, ladrillos de mampostería, mortero de albañilería, materiales asfálticos, etc. (**Figura 2.2**).

**Figura 2.2.** Demolición de edificación.

Fuente: http://proyectoriachuelo.blogspot.com.es/

La fase de demolición selectiva en origen precede al proceso propiamente transformador del RCD en árido reciclado, en el cual en una planta utilizada para tal fin el RCD en forma de escombro sigue una cadena de procesos de machaqueo y cribado, que dependerán del tamaño del producto final elegido (Sánchez de Juan, 2004), pero que, en grandes rasgos, consiste en:

1. Recepción del material.
2. Separación de residuos orgánicos, tóxicos y peligrosos, y su posterior envío a gestores adecuados.
3. Acopio y reutilización de tierras de excavación aptas para su uso.
4. Separación de maderas, plásticos, cartones y metálicos.

5. Tratamiento de material apto para el reciclado, clasificación y reutilización.

6. Eliminaciones de los inertes tratados no aptos para el reciclado y sobrantes del reciclado no utilizado.

Existen dos tipos de plantas de procesado de RCD en función de su movilidad. Las plantas de procesado móviles (**Figura 2.3**) se utilizan en situaciones en donde la reutilización del producto se sitúa en el entorno del lugar de demolición, o donde es más rentable económicamente situar una planta móvil por la lejanía de la deposición del producto procesado.

En cambio, las plantas fijas (**Figura 2.3**) están situadas en lugares donde la deposición final del producto se sitúa en el entorno de la misma para un futuro uso, y a su vez la producción de RCD debe ser alta para permitir la rentabilidad de la misma (núcleos urbanos extensos).

*Planta fija. Fuente: http://sierramadrid.info*

*Planta móvil. Fuente: http://trituradoras-de-roca.com/*

**Figura 2.3.** Plantas de procesado de RCD

Atendiendo a la fracción a conseguir de RCD, el árido reciclado puede ser árido reciclado fino (0,063 mm - 8 mm), árido reciclado grueso (8 mm - 40 mm) y macadam (> 40 mm). Para ello se aplican diferentes cribas en el sistema de procesado, el cual subdividirá posteriormente cada fracción en acopios distintos (**Figura 2.4**).

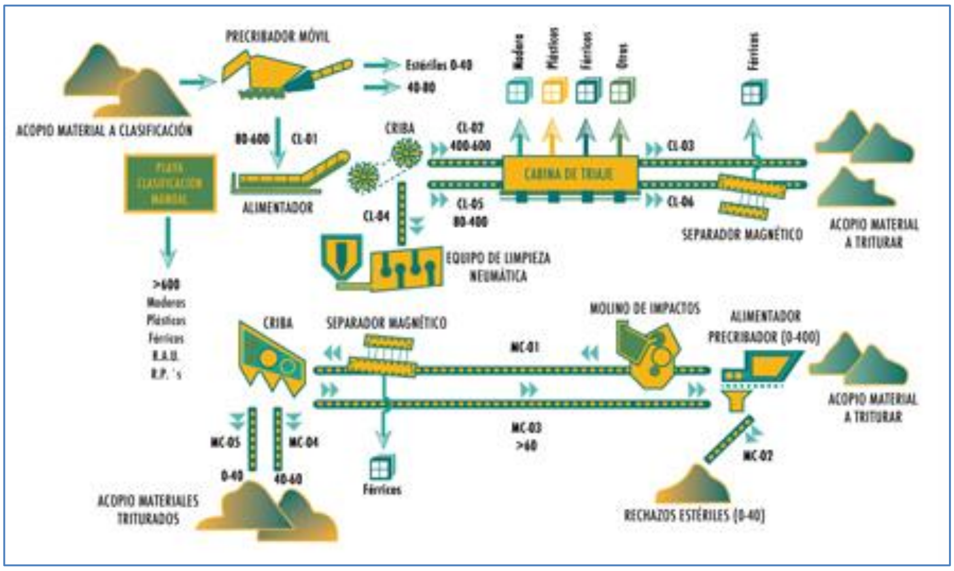


**Figura 2.4.** Procesado de RCD. Fuente: http://www.urbaser.es/

En resumen, el procesamiento de estos residuos de construcción y demolición consiste básicamente en procesos de clasificación, trituración y tamizado, y su naturaleza puede depender de factores como el origen del residuo, propiedades físico-mecánicas y químicas del elemento original y del procesamiento del mismo.

## 2.2. ÁRIDOS RECICLADOS

### *Concepto*

Se puede definir **Árido Reciclado** (AR) como *"el árido obtenido del procesamiento de residuos de construcción y demolición"* (CEDEX, 2010). Los AR son residuos de naturaleza fundamentalmente inerte y, al igual que el árido natural o el artificial, se trata de un material granular utilizado en la construcción.

Las características básicas que definen el material serán las mismas que se tienen en cuenta en el caso de áridos naturales: granulometría, contenido en materia orgánica y sales solubles, equivalente de arena, coeficiente de los ángeles, etc.

La aplicación de los AR el sector de la construcción puede ser tan amplia como la de los áridos naturales, siempre y cuando aquellos cumplan las especificaciones de normativas y de calidad requeridas en cada aplicación.

### *Clasificación*

De acuerdo a su composición, los AR pueden dividirse en diferentes elementos. Agrela et al. (2011) propuso una clasificación en función del porcentaje de cada componente (**¡Error! No se encuentra el origen de la referencia.**).

**Tabla 2.1.** Clasificación de los áridos reciclados según su composición. Fuente: Agrela et al. (2009).

| | Partículas Cerámicas (%) | Partículas Hormigón (%) | Densidad (kg/dm³) | Absorción agua 24 h (%) |
|---|---|---|---|---|
| **Hormigón** | ≤10 | ≥90 | 2,34 - 2,47 | 3,6 -7,3 |
| **Cerámico** | ≤ 10 | ≥70 | 2,22 - 2,58 | 2,1 - 8,79 |
| **Cerámico** | >30 | <70 | 2,06 - 2,39 | 7,21 - 14,36 |

Por otro lado, según la **Norma UNE 146131** *"Áridos para capas granulares y capas tratadas con conglomerantes hidráulicos para su uso en capas estructurales de firmes"*, se distinguen 5 tipos de áridos reciclados:

***-Tipo 1*:** Tratamiento RCD con contenido en productos cerámicos > 90% en peso.

***-Tipo 2:*** Tratamiento RCD con contenido en productos hormigón > 90% en peso.

***-Tipo 3*:** Tratamiento RCD con contenido en productos pétreos > 90% en peso.

***-Tipo 4A*:** Mixtos: Mezclas de cerámicos, hormigón y pétreos.

***-Tipo 4B*:** Mixtos: Mezclas de los tipos anteriores con áridos naturales.

***-Tipo 4C*:** Mixtos: Mezclas de los tipos anteriores con áridos artificiales.

***-Tipo 5A*:** Mezclas de los tipos 1 al 4 con proporciones >10% en peso de materiales bituminosos.

***-Tipo 5B*:** Mezclas de los tipos 1 al 4 con proporciones <10% en peso de materiales bituminosos.

Respecto a la tipología de los áridos reciclados en función de su tamaño de partículas, Auxi Barbudo (Barbudo, A., 2012) expone en su Tesis Doctoral la siguiente clasificación:

***A) Zahorras recicladas:*** materiales granulares de granulometría continua, normalmente entre 0-40 mm.

***B) Gravas recicladas:*** áridos con tamaño de partículas superior a 4mm. Suele diferenciarse, al igual que los áridos naturales, entre gravilla reciclada (4-8 mm) y grava reciclada (> 8 mm).

***C) Arenas recicladas:*** son los áridos con tamaño de partículas inferior a 4 mm, también llamados áridos reciclados finos. Puede diferenciarse entre arenas gruesas (> 2 mm), y arenas finas (< 2 mm).

***D) Filler:*** áridos reciclados con tamaño inferior a 0,063 mm. Este tipo de áridos se suele encontrar impregnado en otras partículas, repercutiendo negativamente en sus propiedades.

## *Árido reciclado de hormigón*

El **Árido Reciclado de Hormigón** (ARH) suele ser heterogéneo en sus propiedades debido al elevado número de factores que lo afectan, como su naturaleza en origen, la presencia de impurezas, o el tipo de trituración y cribado.

Suele presentar una densidad no excesivamente baja (entre 2,1-2,6 kg/dm$^3$), aunque inferior a un árido natural de fracción granulométrica similar. Esta reducción de densidad puede ser debido esencialmente a la pasta de mortero adherido a las partículas que conforman el ARH (Debied F. et al., 2010, Etxeberría et al., 2007).

Por este mismo factor, el ARH suele ser un material poroso (Etxeberría et al., 2007), con elevados valores de absorción respecto al árido natural (entre 6-12% según sea fracción gruesa o fina). Esta afirmación queda corroborada con los datos obtenidos por otros autores, quien obtuvieron valores más altos de absorción con porcentajes más elevados de mortero adherido (Safiullah Omary et al., 2016, Silva et al., 2014, Zhen-Hua y Poon, 2014).

Respecto a la resistencia a la abrasión y desgaste, suelen obtenerse valores de Los Ángeles entre 33-45% (Yuwadee Zaetang et al. 2016, Fatih Özalp et al., 2016, De Brito et al., 2016.) debido también a la presencia del mortero adherido, siendo por lo tanto este elemento, un determinante principal en la calidad de este árido reciclado (Safiullah Omary et al., 2016). El coeficiente de los Ángeles está relacionado con la absorción de agua a 24 horas, aumentando éste en gravas con mayor absorción de agua (Zega et al., 2010, Khaleel et al., 2013.)

Posee múltiples aplicaciones de uso en el sector de la construcción, como su uso en terraplenes, carreteras, o fabricación de hormigón no estructural.

### *Árido reciclado cerámico*

Se clasifican como tales los áridos con un contenido en hormigón inferior al 70% y un contenido en partículas cerámicos superior al 20% (Agrela et al., 2011).

Sus propiedades también suelen variar según la composición. La absorción suele ser elevada, entre 12% y 20% (Poon y Chan, 2007, Debied y Kenai, 2008, Cachim, 2009), y su densidad baja debido a la elevada presencia de partículas cerámicas, pudiendo estar entre 1,5-2% (Debied y Kenai, 2008, Yang et al., 2011). El coeficiente de los Ángeles suele ser elevado (30-50%) (Debied y Kenai, 2008, Aliabdo et al., 2014.) y puede contener elevados índices de sulfatos debido a la presencia de yesos (Barbudo et al., 2012). Suele aplicarse en sub-base y explanadas de carreteras.

Si bien este tipo de áridos suele utilizarse como árido reciclado, el término árido cerámico se encuentra en desuso, siendo sustituido por árido mixto de carácter cerámico.

## *Árido reciclado mixto*

Se considera **Árido Reciclado Mixto** (ARM) aquel cuyo contenido en partículas cerámicas se encuentre sea ≤ 30% y ≥ 0% en peso total y cuyo contenido de partículas de hormigón sea ≥70% y ≤ 90% en peso total (Agrela et al., 2011). Presentan una gran variabilidad de porcentaje de finos (0,5-18%). Su densidad suele encontrarse en torno a 1,8 $kg/dm^3$ debido a la menor densidad de las partículas cerámicas respecto de los áridos naturales y al mortero adherido a las partículas de hormigón reciclado (Safiullah Omary et al., 2016, Silva et al., 2014, Zhen-Hua y C.S. Poon, 2014), y su absorción entre 6-12-%. (Lopez-Uceda et al., 2016, Martinez-Lage et al., 2012, Mas et al., 2012[a],).

El coeficiente de los Ángeles se sitúa entre 34% y 45% (Mas et al., 2012ª, Mas et al., 2012[b], Antonio Lopez-Uceda et al., 2016), estableciendo la EHE-08 un límite de 40% para hormigones no estructurales. Suelen utilizarse en terraplenes, sub-base y explanada de carreteras.

## *Árido reciclado asfáltico*

Es aquel obtenido a partir de carreteras existentes y contiene un elevado número de partículas bituminosas. Es menos común que los anteriores y suele utilizarse en carreteras o reparación de firmes dañados (Barbudo, A., 2012).

## *Destino principal de los áridos reciclados de acuerdo a su tipología*

La Guía de áridos reciclados de residuos de construcción y demolición de Andalucía Central propone una clasificación de acuerdo a la fracción granulométrica de los áridos reciclados con granulometrías que pueden ir desde 0-6 mm a 40-80 mm y sus destinos más comunes (**Tabla 2.2**).

**Tabla 2.2.** Tipología de materiales y de destino. Fuente: Guía de áridos reciclados de Andalucía

| Material | Naturaleza | Destino |
|---|---|---|
| **Arena** | Mixta | Cama de tuberías y tierra vegetal. |
| | Hormigón | Cama de tuberías, mortero de albañilería y hormigón no estructural. |
| **Grava** | Mixta | Relleno de material drenante. |
| | Hormigón | Rellenos, material drenante y hormigón pobre. |
| **Zahorra** | Mixta | Caminos rurales y subbase para carreteras |
| | Hormigón | Caminos rurales y subbase para carreteras, acerados y carril bici |
| **Árido grueso > 32 mm** | Mixta<br>Hormigón | Material drenante |
| **Tierra de excavación** | | Tierra vegetal y rellenos |

## 2.3. RESIDUOS INDUSTRIALES

### *Concepto*

Según la Ley 22/2011 de 28 de Julio, se define **Residuos Industriales** (RI) como *"los residuos resultantes de los procesos de fabricación, de transformación, de utilización, de consumo, de limpieza o de mantenimiento generados por la actividad industrial, excluidas las emisiones a la atmósfera reguladas en la Ley 34/2007, de 15 de noviembre".*

De acuerdo con el Plan Estatal Marco de Gestión de Residuos (PEMAR) 2016-2022, se puede establecer una clasificación de residuos industriales en función de su categoría (**Tabla 2.3**) determinada en la Clasificación Nacional de Actividades Económicas (CNAE, 2009).

**Tabla 2.3.** Residuos industriales de acuerdo con la CNAE

| | Tipo | CNAE |
|---|---|---|
| **1** | Industria de la alimentación, bebidas y tabaco | 10,11,12 |
| **2** | Industria textil, de la confección y curtido | 13,14,15 |
| **3** | Industria de la madera y del corcho | 16 |
| **4** | Industria del papel, artes gráficas y reproducción de soportes grabados | 17,18 |
| **5** | Coquerías y refino de petróleo | 19 |
| **6** | Industria química y de la fabricación de productos de caucho y plástico | 20,21,22 |
| **7** | Industrias de otros productos minerales no metálicos | 23 |
| **8** | Metalurgia y fabricación de productos metálicos, excepto maquinaria y equipo | 24,25 |
| **9** | Fabricación de productos informáticos, electrónicos, maquinaria y material de transporte | 26,27,28,29,30 |
| **10** | Muebles y otras industrias manufactureras. Reparación e instalación de maquinaria y equipo | 31,32,33 |

Respecto a la generación de residuos industriales, la **Tabla 2.4** muestra las cantidades de residuos obtenidas en la industria en el año 2012.

**Tabla 2.4.** Residuos industriales no peligrosos en 2012. Fuente: INE

| Tipo de residuos no peligrosos | Cantidad (t) |
|---|---|
| Otros residuos minerales | 3.472.731 |
| Residuos de combustión | 1.832.823 |
| Residuos metálicos, férreos | 1.497.589 |
| Residuos animales y de productos alimenticios mezclados | 926.878 |
| Residuos de papel y cartón | 824.000 |
| Residuos mezclados e indiferenciados | 755.004 |
| Residuos vegetales | 734.894 |
| Residuos de madera | 477.255 |
| Residuos metálicos mezclados | 464.015 |
| Lodos de efluentes industriales (secos) | 455.648 |
| Lodos comunes | 279.510 |
| Resto | 1.510.231 |
| Total | **13.230.578** |

El mayor volumen de residuos industriales procede de la industria de extracción de residuos minerales seguido de los residuos generados mediante combustión y residuos metálicos. Otro tipo de residuos, como los residuos vegetales o residuos procedentes de la industria de la madera, son generados en menor magnitud.

Sin embargo, en Andalucía, este tipo de residuos, llamado biomasa, se generan en mayor proporción debido a la industria procedente de la explotación el olivar y otras industrias agroalimentarias, por lo que su reciclaje tiene mayor sentido.

## 2.4. CENIZAS DE BIOMASA

### *Concepto*

Según la Orden ITC/2877/2008 se define **Biomasa** como *"la fracción biodegradable de los productos, subproductos y residuos procedentes de la agricultura (incluidas las sustancias de origen vegetal y de origen animal), de la silvicultura y de las industrias conexas, así como la fracción biodegradable de los residuos industriales y municipales"*. Este Real Decreto realiza a su vez una clasificación de los diferentes tipos de biomasa:

- **Cultivos energéticos agrícolas:** biomasa de origen agrícola producida con fines energéticos mediante su cultivo y cosecha.
- **Cultivos energéticos forestales:** biomasa procedente del aprovechamiento de masas forestales producida mediante cultivo y cosecha con fines energéticos.
- **Residuos de actividades agrícolas:** biomasa procedente el procesado de productos agrícolas, incluyendo la procedente de procesos de eliminación de cascara. Destacan los residuos agrícolas herbáceos y residuos agrícolas leñosos (poda de especies leñosas como olivar, viñedos y frutales).
- **Residuos de actividades de jardinería:** biomasa procedente de limpieza y mantenimiento de jardines.
- **Biomasa procedente de instalaciones industriales del sector forestal:** residuos de industrias forestales de primera transformación, residuos de industrias forestales de segunda transformación, y otros.

## *Proceso y transformación*

La biomasa se utiliza principalmente en el sector de la energía renovable como biocombustible para la generación de energía eléctrica. El consumo de energía eléctrica a partir de energía renovable está evolucionando favorablemente, aumentando progresivamente (**Tabla 2.5**).

**Tabla 2.5.** Evolución del consumo primario de energías renovables. Fuente: Agencia Andaluza de la Energía.

| | Biomasa | Hidráulica | Eólica | Solar Term. | Solar Fotov. | Termosolar | Total ktep |
|---|---|---|---|---|---|---|---|
| 2003 | 846,4 | 87,9 | 41,5 | 17,4 | 1 | 0 | 994,3 |
| 2004 | 849 | 78,3 | 44,5 | 19,8 | 1,5 | 0 | 993,2 |
| 2005 | 867,2 | 54,5 | 78 | 22,5 | 1,6 | 0 | 1.023,80 |
| 2006 | 670,9 | 39,6 | 89,7 | 27,1 | 1 | 0 | 828,3 |
| 2007 | 901,7 | 34,4 | 104,6 | 32,4 | 4,6 | 2.9 | 1.060,50 |
| 2008 | 1266,7 | 41,6 | 214,4 | 39 | 36 | 8.8 | 1.606,50 |
| 2009 | 1155,8 | 70,1 | 375,7 | 44,2 | 122,6 | 45,4 | 1.813,80 |
| 2010 | 1409,8 | 126,7 | 510,1 | 52,2 | 97,4 | 188,5 | 2.384,70 |
| 2011 | 1437,4 | 103,7 | 538 | 56,4 | 121,8 | 403,9 | 2.661,30 |
| 2012 | 1647,9 | 61,8 | 495,8 | 61 | 133,1 | 896,4 | 3.296,10 |
| 2013 | 1387,1 | 111,9 | 603,9 | 67,1 | 137,9 | 1049 | 3.356,90 |
| 2014 | 1629,3 | 81,6 | 557,5 | 72,7 | 137,8 | 1.189,20 | 3.668,10 |

Respecto al consumo primario de biomasa como energía renovable, en 2014 fue del 44,4%, siendo por tanto la energía renovable más utilizada **(Figura 2.5**).

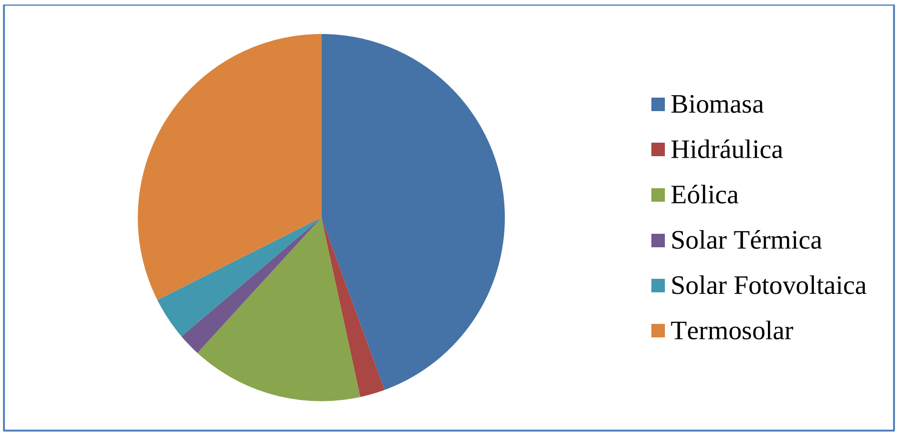


**Figura 2.5**. Proporción del consumo primario de energías renovables en 2013. Fuente: Agencia Andaluza de la Energía.

La biomasa generada a partir de residuos agrícolas leñosos es la más utilizada para la producción de energía en la Andalucía. En esta región está muy extendida la producción de energía a partir de esta materia prima debido a la gran industria agroalimentaria y del sector del olivar existente.

Atendiendo al nivel de aprovechamiento energético, la biomasa se puede clasificar del siguiente modo (Agencia Andaluza de la Energía, 2013):

- **Residuos agrícolas:** todos los residuos orgánicos y restos vegetales generados de cultivos agrícolas de campo o invernadero. Está compuesto de podas de cultivos arbóreos.
- **Residuos forestales**: todos los productos o subproductos derivados de tratamientos silvícolas (leñas, ramas y matorrales) que se realizan en las superficies forestales que no tengan como fin principal su uso energético.
- **Residuos ganaderos**: todos los residuos orgánicos generados por las especies ganaderas.
- **Residuos y subproductos industriales:** todos los residuos orgánicos generados por la industria.

En Andalucía, los principales residuos de biomasa son los residuos agrícolas y residuos forestales. El principal residuo agrícola generado es la biomasa del olivar, el cual destaca como principal tipo de residuo debido a la alta producción de aceite de oliva. La producción de aceite de oliva genera una serie de subproductos residuales utilizados para la producción de energía, como son el orujo, orujillo, hueso de aceituna y poda de olivar. Sin embargo, los residuos forestales leñosos más destacados son la poda de árboles frutales, cítricos, vid, olivar, chopo y eucalipto.

La producción de energía a partir de biomasa es generada en plantas generadoras construidas para tal fin, cuyo proceso de producción de generación queda descrito en la (Hinojosa et al., 2014) Esencialmente, una planta de biomasa está compuesta por los siguientes elementos esenciales para la generación de energía: tolva de suministro, línea de combustible, parrilla de combustión, pistones hidráulicos y sistema de evacuación (**Figura 2.6**).

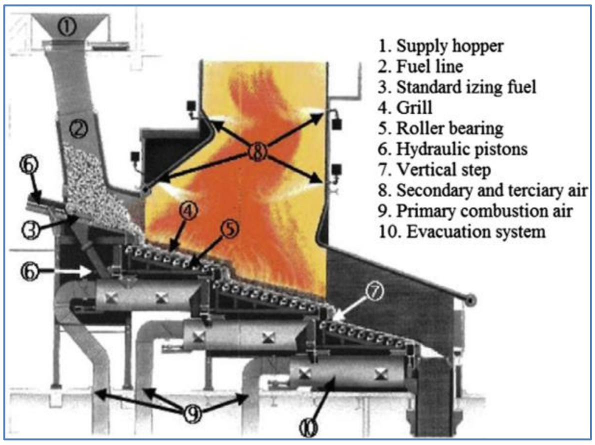


**Figura 2.6.** Planta de producción de electricidad a partir de biomasa. Fuente: Hinojosa et al. 2014.

Las plantas están diseñadas para la generación de energía a partir de sobrecalentamiento de vapor mediante el proceso de combustión de la biomasa y la recuperación de calor de los gases. La biomasa se introduce en el sistema mediante un proceso automático de alimentación desde el punto de almacenamiento. Tras la finalización del proceso, el residuo generado se elimina del sistema mediante un proceso de evacuación en forma húmeda generando un acopio húmedo. Cabrera et al. (2014) (**Figura 2.7**).

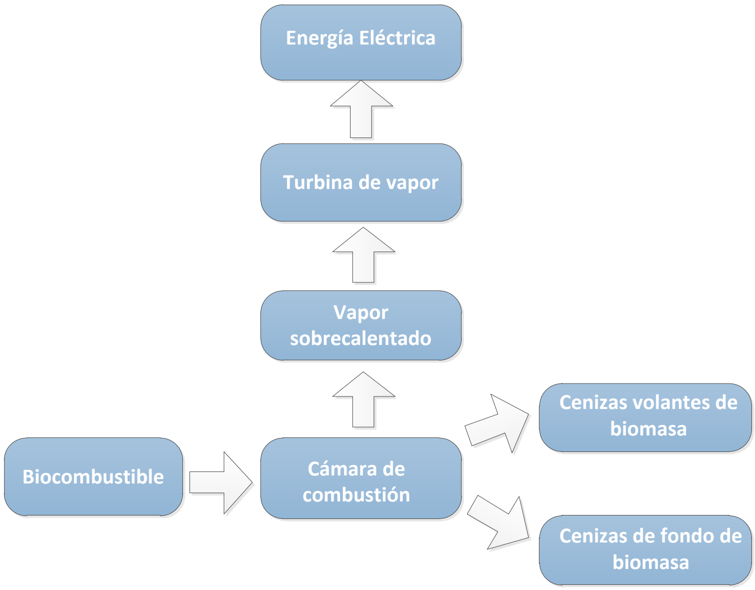


**Figura 2.7.** Proceso de producción de energía con biomasa. Fuente: Cabrera et al. 2014.

## *Cenizas de fondo de biomasa*

Dos subproductos se generan en el proceso de combustión de biomasa (Hinojosa et al., 2014): ***cenizas volantes de biomasa*** (CVB**),** las cuales se extraen del sistema mediante fuerza centrífuga por vía aérea, y ***cenizas de fondo de biomasa*** (CFB) residuo que queda en el fondo de la cámara y se extrae vía húmeda en acopio, tal como se ha descrito anteriormente.

La CFB se caracteriza por su elevada porosidad y su reducida densidad (Cabrera et al., 2014). Su distribución granulométrica se asemeja a una arena natural (AN) y su capacidad de absorción de agua es muy alta (**Figura 2.8**). También posee una alta susceptibilidad al desgaste (friabilidad) y un elevado contenido en materia orgánica (Hinojosa et al., 2014), relacionada esta última con la eficiencia de combustión en planta.

**Tabla 2.6.** Propiedades de CFB. Fuente: Cabrera et al., 2014; Hinojosa et al., 2014.

| Absorción | Densidad | Friabilidad | Materia orgánica |
|---|---|---|---|
| 30 | 1,8 | 30 | 7,5 |

La elevada absorción y materia orgánica pueden influir en las propiedades mecánicas y de durabilidad de elementos constructivos como hormigones, morteros y materiales tratados con cementos fabricados con este tipo de residuo, por lo que se ha de tener especial cuidado en su aplicación.

### *Aplicación de cenizas de biomasa en materiales tratados con cemento*

En los últimos años, la necesidad de dar una salida medioambiental a los residuos procedentes de la combustión de biomasa para la generación de energía ha dado lugar a varias investigaciones que han tenido como objetivo estudiar las propiedades físico-químicas de estos residuos y sus posibilidades de uso en materiales tratados con cemento, como suelo-cemento, hormigones y morteros.

Rajamma et al. (2009) estudiaron las propiedades de CVB para su aplicación en materiales tratados con cemento. A su vez, Cabrera et al. (2014) realizaron una investigación para analizar las propiedades de las CFB y sus posibilidades de uso en la construcción e ingeniería civil.

Hinojosa et al. (2014) analizaron las propiedades químicas de CFB y sus posibilidades de aplicación. Por su parte, Wang et al. (2008) investigaron la influencia de CVB en hormigones como sustituto del cemento.

Cuenca et al. (2013) adicionaron CVB como filler para estudiar el comportamiento de hormigones auto-compactantes, mientras que Carrasco et al (2014) aplicaron sustituciones de entre un 10% y un 90% en peso de cemento por CFB para la creación de bloques de construcción.

Respecto a su aplicación a morteros, Maschio et al. (2011) aplicaron reemplazos de cemento por CVB y CFB al 5, 10, 15, 20 y 30% en masa para estudiar su comportamiento mecánico. Por otro lado, Modolo et al. (2015) investigaron la influencia de CFB en morteros adhesivos, aplicando tasas de sustitución de AN por CFB de 0, 25, 50 y 100%.

La escasa bibliografía existente respecto de la aplicación de CFB en hormigones y su influencia en los mismos permite plantear la posibilidad de realizar un análisis en profundidad que arroje luz a las posibilidades de uso de este tipo de residuos.

## 2.5. CONSIDERACIONES AMBIENTALES

En el proceso de investigación de RCD y CFB, así como de cualquier otro residuo para su reutilización, no sólo ha de tenerse en cuenta el aspecto físico, químico o mecánico que éstos puedan influir en las propiedades mecánicas y de durabilidad de diferentes elementos constructivos, sino que ha de ser tenido muy en cuenta el posible efecto contaminante que éstos residuos puedan influir en el medio ambiente.

En general, los RCD son residuos de naturaleza inerte. Sin embargo, pueden contener algunos materiales peligrosos, como metales pesados u otros elementos contaminantes (Galvín et al., (2012). Los materiales que pueden tener mayor cantidad de elementos contaminantes son (CEDEX, 2010):

- Adhesivos, másticos y sellantes.
- Aditivos de hormigón.
- Envases que hayan contenido sustancias peligrosas (disolventes, pinturas, adhesivos).
- Materiales a base de amianto, en forma de fibra respirable.
- Elementos a base de yeso.
- Emulsiones alquitranadas.

Existen un elevado número de métodos para evaluar el impacto ambiental de materiales que puede incorporar materiales secundarios, como los ensayos de lixiviación, definiéndose lixiviación como *"proceso por el cual contaminantes orgánicas o inorgánicos son liberados de una fase sólida a una fase acuosa"* (Barbudo, 2012). Este tipo de ensayos simulan la infiltración de agua procedente de lluvia a través de los materiales expuestos en el exterior. En este caso, el agua puede transportar materiales contaminantes, liberándose el material contaminante de una fase sólida a una fase acuosa. Aunque ha de ser tenido en cuenta la cantidad de elementos contaminantes presentes en la matriz, el factor más importante a la hora de establecer el impacto ambiental del material principal es la susceptibilidad del material contaminante de ser liberado de la matriz por disolución y lixiviación. Es por esto que la utilización de métodos de lixiviación es una herramienta adecuada para determinar el impacto ambiental del material analizado (Galvín et al., 2014).

Existe normativa vigente en la que se definen los procedimientos, métodos de admisibilidad, y valores límites de residuos para su deposición en vertederos Directiva Europea 2003/33/CE). Por tanto, todo material susceptible de ser contaminante debe ser analizado mediante ensayos de lixiviación para determinar las concentraciones lixiviables de sulfatos, cloruros y fluoruros, y elementos como Hg, Cu, Ba, As, Cd, et. A este respecto, los valores límite para la clasificación de cualquier material como inerte, no peligroso o peligroso, se muestran en la **Tabla 2.7**.

Para poder estimar la susceptibilidad a la lixiviación a largo plazo de un determinado elemento bajo las condiciones más desfavorable, se necesita determinar la cantidad de ese elemento a ser lixiviado (Barbudo, 2014). Para ello ha de conocerse la concentración máxima lixiviable de un elemento, o "concentración potencialmente lixiviable" (Engelsen et al., 2010).

**Tabla 2.7.** Clasificación de peligrosidad de residuos en función de la cantidad lixiviada (Para L/S 10Kg/l) para admisión en vertedero. Fuente: Directiva Europea 2003/33/CE

| | Concentración lixiviada (mg/kg) | | |
|---|---|---|---|
| | **Inerte** | **No peligroso** | **Peligroso** |
| Cr Total | 0.5 | 10 | 70 |
| Ni | 0.4 | 10 | 40 |
| Cu | 2 | 50 | 100 |
| Zn | 4 | 50 | 200 |
| As | 0.5 | 2 | 25 |
| Se | 0.1 | 0.5 | 7 |
| Mo | 0.5 | 10 | 30 |
| Cd | 0.04 | 1 | 5 |
| Sb | 0.06 | 0.07 | 5 |
| Ba | 20 | 100 | 300 |
| Hg | 0.01 | 0.2 | 2 |
| Pb | 0.5 | 10 | 50 |
| Sulfatos | 1000 | 20000 | 50000 |
| Fluoruros | 10 | 150 | 500 |
| Cloruros | 800 | 15000 | 25000 |

Como se ha descrito anteriormente, ha de tenerse en cuenta la diferencia entre "concentración total" y "evolución de la lixiviación con el tiempo (Hidalgo y Alonso, 2005), siendo este último el factor relacionado con el impacto ambiental y no el primero. Para comprender correctamente este concepto, Van der Sloot y Kosson (2003) proponen la siguiente gráfica (**Figura 2.8**), donde la concentración total y la concentración potencialmente lixiviable no son tan limitantes como la evolución de lixiviación en el tiempo.

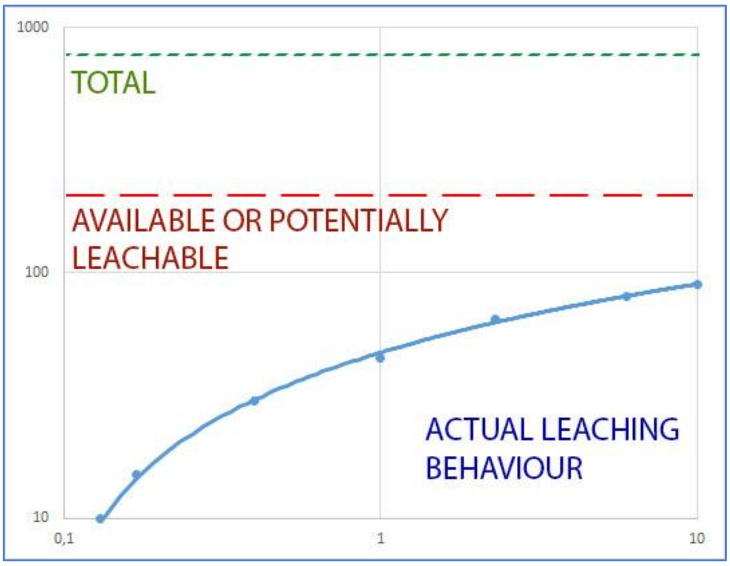


**Figura 2.8.** Concentración total - Lixiviación. Fuente: Vander Sloot y Kosson (2003).

Existen varios tipos de ensayos de lixiviación en función del comportamiento de los materiales frente a lixiviación. Los **ensayos de caracterización básica** se realizan para obtener información fundamental del comportamiento a corto y largo plazo, como la composición del medio lixiviante, pH, potencial redox, parámetros físicos, etc. Los **ensayos de conformidad** se encargan para determinar si un material produce lixiviaciones en concentraciones de elementos por debajo de unos valores de referencia. Por último, **los ensayos de verificación in situ** se utilizan para estudiar si un material tiene un comportamiento similar a los ensayos de conformidad.

Este tipo de ensayos suelen realizarse en laboratorio, debido al costo económico y la complejidad que acarrearía la realización este tipo de ensayos en condiciones reales, y deben predecir el impacto ambiental derivado de la lixiviación a largo plazo para una adecuada valoración medioambiental.

# CAPÍTULO III

## *HORMIGONES RECICLADOS*

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## *HORMIGONES RECICLADOS*

En el siguiente capítulo se presenta el estado del arte en la investigación de hormigones fabricados con materiales reciclados. Se presentan en primer lugar las investigaciones más relevantes cronológicamente seguido de la valoración de propiedades de los hormigones de acuerdo con los datos publicados.

### 3.1. ANTECEDENTES

#### *Hormigones fabricados con áridos reciclados de hormigón*

El comportamiento de hormigones fabricados con ARH ha sido ya investigado por diversos autores en las últimas décadas.

Bairagi et al. (1993) estudiaron el comportamiento de hormigones con sustituciones de áridos naturales por ARH en tasas de sustitución de 0, 25, 50, 75 y 100%. Topçu (1997) examinó propiedades físicas y mecánicas de hormigones fabricados con sustituciones de árido natural por ARH de 0, 30, 50, 70 y 100%.

Por su parte, Limbachiya et al. (2000) utilizaron ARH en la fabricación de hormigón reciclado de alta resistencia utilizando 0, 30, 50 y 100% de incorporación de ARH de granulometría gruesa.

Sagoe-Crentsil et al. (2001) realizaron una investigación sobre el comportamiento mecánico y de durabilidad en hormigones fabricados con un 100% de incorporación de ARH.

Por otro lado, Katz (2003) estudió las propiedades mecánicas y de durabilidad de hormigones fabricados con áridos reciclados triturados a diferentes edades a partir de hormigones convencionales fabricados en laboratorio, mientras que Poon et al. (2004) analizaron la influencia del tipo de humedad de los áridos naturales y reciclados en la consistencia del hormigón fresco y la resistencia a compresión a 3, 7 y 28 días ofreciendo resultados similares de resistencia a compresión hasta una sustitución máxima del 50%.

Etxeberría et al. (2007) utilizó cuatro tasas de incorporación de AR (0, 25, 50 y 100%) para analizar su influencia y el proceso de producción en las propiedades de los hormigones fabricados.

Otras investigaciones fueron realizadas con el fin de optimizar el uso de AR en la fabricación de hormigones. Barbudo et al. (2013) estudiaron la influencia de reductores de la relación a/c en las propiedades mecánicas de hormigones fabricados con ARH aplicando tasas de sustitución de áridos ARH de 0, 20, 50 y 100%, y varios tipos de super-plastificantes. Cartuxo et al. (2015) observaron la influencia de un plastificante y un super-plasificante en las propiedades mecánicas y de durabilidad en hormigones fabricados con sustituciones de AN por ARH de granulometría fina (0, 10, 30, 50 y 100% de sustitución).

Corinaldesi y Moriconi (2009) analizaron las propiedades mecánicas y de durabilidad de hormigones fabricados con ARH de granulometría gruesa y fina y con adiciones minerales (15 y 30% en peso de cemento).

Kou et al. (2011) observaron el comportamiento mecánico y de durabilidad de hormigones fabricados con tasas de sustitución de 0, 50 y 100% de áridos naturales por ARH y con incorporaciones de adiciones minerales.

### *Hormigones fabricados con áridos reciclados mixtos*

El amplio conocimiento aportado por la comunidad investigadora en todo el mundo sobre el comportamiento de hormigones fabricados con áridos reciclados de hormigón condujo a la realización de numerosas investigaciones en las que se analizó la influencia de áridos reciclados de tipo mixto.

Agrela et al. (2011) realizaron una investigación para estudiar las propiedades de ARM y la correlación entre sus propiedades para su aplicación en hormigones.

Yang et al. (2011) aplicaron diferentes tasas de incorporación de ladrillos triturados y ARH combinados para estudiar sus propiedades físicas y mecánicas.

Por su parte, Mas et al. (2012[b]) estudiaron las propiedades mecánicas de hormigones no estructurales fabricados con diferentes cantidades de ARM. Por su parte, Martinez-Lage et al. (2012) por su parte evaluaron las propiedades mecánicas de hormigones en masa aplicando sustituciones de gravas naturales por ARM (0, 50 y 100% de sustitución).

Otros autores como César Medina et al. (2014) fabricaron hormigones con tasas de sustitución de 0, 25 y 50% de gravas naturales por ARM con y sin partículas flotantes para estudiar sus propiedades físico-mecánicas.

### *Hormigones fabricados con áridos reciclados de granulometría fina*

El espectro granulométrico de los áridos reciclados no se limita sólo a tamaños de partículas superiores a 4 mm, sino que la producción de áridos reciclados genera partículas que van desde los 0 mm a los 4 mm, permitiendo con ello clasificar otro subproducto como árido reciclado fino, tanto de hormigón como mixto.

Dada la entidad del árido reciclado fino, numerosas investigaciones han sido realizadas para aplicar este tipo de árido reciclado en hormigones. Khatib (2005) analizaron las propiedades físico-mecánicas de hormigones fabricados con sustituciones de 0, 25, 50 y 100% de AN por áridos reciclados finos, tanto de hormigón como de ladrillos triturados.

Evangelista y Brito (2007) estudiaron el comportamiento mecánico de hormigones fabricados con áridos reciclados finos aplicando tasas de sustitución de AN por árido reciclado fino de hormigón de 0, 10, 20, 30, 50 y 100%.

Debied y Kenai (2008) aplicaron por su parte sustituciones de áridos naturales por áridos reciclados finos obtenidos por trituración de ladrillos para estudiar sus propiedades mecánicas y de durabilidad.

Evangelista y Brito (2010) realizaron una investigación para observar las propiedades de durabilidad de hormigones fabricados con tasas de incorporación de áridos reciclados finos de 0, 30 y 100%. Por otro lado, Alves et al. (2014) observaron las propiedades mecánicas de hormigones estructurales con sustituciones de AN por áridos reciclados finos de tipo cerámico (0, 20, 50 y 100% de sustitución).

### *Hormigones de otra tipología*

La investigación de hormigones con aplicaciones de áridos reciclados no se limita sólo a hormigones convencionales. Otras investigaciones han sido desarrolladas aplicando áridos reciclados en hormigones auto-compactantes o ligeros.

Kou y Poon (2009) estudiaron las propiedades mecánicas de hormigones auto-compactantes fabricados con ARH, tanto en su fracción fina como gruesa, con tasas de sustitución de árido naturales por ARH de 0, 25, 50, 75 y 100%.

Zoran Jure Grdic y et al. (2010) analizaron las propiedades de hormigón fresco y endurecido en hormigones auto-compactantes aplicando tasas de incorporación de ARH de 0, 50 y 100%. Por otra parte, Güneyisi et al. (2016) investigaron las propiedades de hormigones auto-compactantes fabricados con fracciones gruesas y finas de árido reciclado de hormigón.

Respecto a hormigones ligeros, Paulo Roberto Lopes Lima et al. (2010) estudiaron las propiedades físico-mecánicas de hormigones ligeros fabricados con áridos reciclados y residuos industriales del calzado con diferentes tasas de sustitución.

Otras investigaciones sobre el estudio de propiedades de hormigones reciclados se han realizado utilizando subproductos o materiales reciclados de naturaleza diferente a la de los áridos reciclados procedentes de la construcción y demolición.

De Castro y de Brito (2013) aplicaron tasas de sustitución de áridos naturales por áridos reciclados de cristal triturados de 0, 5, 10 y 20% para analizar sus propiedades mecánicas y de durabilidad. Bravo y de Brito (2012) fabricaron hormigones aplicando sustituciones de 5, 10 y 15% de áridos naturales por partículas trituradas de neumáticos para estudiar sus propiedades mecánicas y de durabilidad.

Por otra parte, Güneyisi et al. (2016) investigaron las propiedades de hormigones auto-compactantes fabricados con fracciones gruesas y finas de ARH.

## 3.2. PROPIEDADES DE LOS HORMIGONES RECICLADOS

### *Resistencia a compresión*

Se puede afirmar, de forma general, que la resistencia a compresión se reduce con la incorporación de áridos reciclados, tanto de ARH como de ARM. Kou et al. (2012) obtuvieron pérdidas de resistencia a compresión para tres series de amasadas aplicando tasas de sustitución de áridos naturales gruesos por áridos reciclados gruesos de hormigón de baja calidad de 0, 20, 50 y 100%, siendo esta proporción mayor cuanto mayor fue la tasa de sustitución.

Kwan et al. (2012) aplicó tasas de incorporación de ARH de 0, 15, 30, 60 y 80%, obteniendo pérdidas de resistencia a compresión para todas las edades de medición. Sin embargo, las diferencias para un 15% de sustitución a 28 días de edad no fueron significativamente grandes, estando este resultado de acuerdo con otros autores, que obtuvieron pérdidas de resistencia a compresión no significativas para sustituciones de áridos naturales gruesos por ARH de hasta un 20% (Etxeberría et al., 2007[b], Barbudo et al., 2013).

La pérdida de resistencia a compresión en hormigones con ARH puede ser debida a muchos factores. Un factor esencial es la calidad del hormigón original y la resistencia a compresión que el hormigón de origen posee (Tabsh y Abdelfatah (2009). Otro factor primordial es la cantidad del mortero adherido a las partículas de hormigón trituradas presente y la calidad del mismo (Etxeberría et al., 2007[a]). Este mortero aumenta significativamente la absorción de agua, la cual debe tenerse en cuenta en la fabricación de hormigones con ARH, reduce la densidad del hormigón debido a su elevada porosidad y genera zonas de debilidad el hormigón por su elevada susceptibilidad a la trituración (Sanchez de Juan y Alaejos, 2009, Kou et al., 2011, Saravanakumar et al., 2016).

Al igual que ocurre en hormigones con contenido de ARH, la resistencia a compresión en hormigones con ARM gruesos suele verse reducida a medida que aumenta la tasa de incorporación. Muchas investigaciones apuntan a esta afirmación. Mas et al. (2012[a]) obtuvieron pérdidas de resistencia a compresión con la incorporación de ARM para las tres series analizadas. Asimismo, Martinez-Lage et al. (2012) obtuvieron pérdidas de resistencia a compresión respecto del hormigón de control para tasas de sustitución de áridos naturales por ARM de 50 y 100% en dos series. Por otro lado, Mas et al. (2012[b]) concluyó en su investigación que la inclusión de cemento resistente al ataque de sulfatos disminuye la pérdida de resistencia a compresión debida a la incorporación de ARM.

La influencia de ARM en hormigones es debido a varios factores como la calidad del elemento original, a la presencia del mortero adherido (presumiblemente mayor debido al mortero de albañilería), a la elevada porosidad de las partículas cerámicas que aportan mayor absorción de agua y a la susceptibilidad a la trituración del mortero adherido y las partículas cerámicas (Medina et al, 2014, Lopez-Uceda et al., 2016).

### *Resistencia a flexión*

Del mismo modo que ocurre con la resistencia a compresión, por norma general la resistencia a flexión se reduce con la incorporación de áridos reciclados. Katz (2003) obtuvo pérdidas de resistencia a flexión desde un 12 hasta un 32% para hormigones con 100% de ARH y cemento Portland.

Topçu y Sengel (2004) aplicaron tasas de sustitución de AN por ARH de 30, 50, 70 y 100% obteniendo pérdidas de resistencia a flexión de hasta un 20%.

Debied y Kenai aplicaron sustituciones de áridos naturales por ladrillos triturados en tasas de sustitución de 0, 25, 50, 75 y 100%. Las pérdidas de resistencia a flexión fueron desde 15% hasta un máximo del 40%.

Por otro lado, Jian Yang et al. (2011) combinaron diferentes porcentajes de ARH y ladrillos triturados en la fabricación de hormigones reciclados. Las pérdidas de resistencia a 28 días no superaron el 10% para un 100% de sustitución de grava natural ARH y un 6% para una combinación de ARH y ladrillos triturados.

Al igual que ocurre con la resistencia a compresión, la reducción de la resistencia a flexión tiene su origen en diversos factores, como la propia calidad del hormigón original, la presencia del mortero adherido que provoca un aumento de la porosidad y disminución de la densidad o la baja resistencia a la trituración de las partículas cerámicas.

### *Densidad del hormigón endurecido*

Como norma general, la densidad del hormigón endurecido fabricado con áridos reciclados se reduce en comparación con un hormigón convencional, mientras que la porosidad experimenta el efecto contrario, aumenta conforme aumenta la cantidad de áridos reciclados.

Khatib (2005) obtuvo descensos en los valores de densidad a diferentes edades en hormigones con incorporaciones de áridos reciclados finos, siendo mayor conforme mayor fue la cantidad de árido reciclado. Martinez-Lage et al. (2012) por su parte, experimentaron pérdidas de densidad de hasta un 10% para tasas de sustitución del 100% de áridos naturales por áridos reciclados.

Duan y Poon (2014) obtuvieron pérdidas de densidad en hormigones con áridos reciclados respecto al hormigón de referencia. Del mismo modo, César Medina et al. (2014) obtuvieron pérdidas de densidad proporcionales al aumento de la cantidad de ARM.

La principal causa de las reducciones de densidad y aumento de la capacidad de absorción en hormigones reciclados se debe al mortero adherido, debido a su elevada porosidad (Marta Sánchez de Juan y Pilar Alaejos Gutiérrez, 2009).

La densidad de las partículas también es considerada un factor clave en la densidad del hormigón endurecido (Matías et al. 2013). Por este motivo, los hormigones fabricados con ARM experimentan menor densidad debido a su contenido en partículas cerámicas.

### *Velocidad de impulsos ultrasónicos*

La velocidad e impulsos ultrasónicos (UPV) es una propiedad del hormigón endurecido que depende de la calidad del hormigón en general, es decir, de su grado de compactación, porosidad, calidad de los áridos, resistencia del cemento, etc. Es, por tanto, una propiedad muy ligada a otras propiedades como la resistencia a compresión y la densidad del hormigón endurecido (Trnitk et al., 2009).

Kou et al. (2011) concluyó que los valores de UPV fueron menores en hormigones con incorporaciones de áridos reciclados, estando este resultado de acuerdo con el obtenido por Rio LMdel et al. (2004).

A su vez, Kwan et al. (2012) obtuvo similares resultados, en los que los valores UPV se redujeron con el aumento de RA en los hormigones fabricados.

## *Penetración de agua bajo presión*

Por lo general, la penetración de agua bajo presión aumenta en hormigones reciclados respecto del hormigón de referencia.

Este aumento en la penetración de agua bajo presión tiene relación con una mayor porosidad de las partículas de hormigón y cerámicas y a una menor compactibilidad y calidad en general del hormigón.

Correia et al. (2006) obtuvieron aumentos en la penetración de agua en hormigones con un 30% de partículas cerámicas. Por otro lado, Mas et al. (2012)[a] concluyeron que el aumento de la penetración de agua es proporcional a la cantidad de ARM en hormigones reciclados.

## *Difusión del ión cloruro*

Análogamente a la penetración de agua bajo presión, la difusión del ión cloruro aumenta en hormigones reciclados respecto a los hormigones convencionales.

Las causas de este aumento de penetración también están relacionadas con un mayor grado de porosidad en las partículas de hormigón y cerámicas por el mortero adherido a sus partículas y a un menor grado de compactación de los hormigones reciclados respecto del hormigón de control.

Evangelista y De Brito (2010) obtuvieron aumentos de penetración del ión cloruro de hasta un 34% para tasas de sustitución de AN por árido reciclado de fino de un 30%. Zhan and Zong (2013) observaron un aumento en la difusión del ión cloruro para hormigones reciclados con un 30% de RA.

Kou et al. (2011) también encontraron incrementos significativos en la difusión del ión cloruros para hormigones con incorporaciones de RA.

### *Retracción del hormigón*

La retracción del hormigón es una propiedad que queda influenciada por la incorporación de RA. Como normal general, los valores de retracción aumentan conforme mayor en la tasa de RA en el hormigón reciclado pudiendo estar este fenómeno relacionado el mortero adherido a las partículas trituradas.

Katz (2003) concluyó que los hormigones con ARH experimentaron una mayor retracción del hormigón respecto del hormigón de control. Del mismo modo, Sagoe-Crentsil et al. (2001) encontraron aumentos de retracción de hasta un 25% en hormigones reciclados respecto del hormigón de referencia.

Domingo-Cabo et al. (2009) obtuvieron mayor retracción en hormigones fabricados con RA respecto del hormigón de referencia, siendo más significativo para tasas de sustitución del 100%.

## 3.3 Valoraciones

En base a la bibliografía analizada, parece factible seguir investigando y analizando las posibilidades de aplicación tanto de ARH como de ARM mediante la optimización de éstos, como la posibilidad de adición de cemento para igualar las propiedades mecánicas, la aplicación de ARM bajo varias tasas de sustitución o la aplicación de áridos reciclados todo-uno.

A su vez, tal como se comenta en el capítulo anterior, los residuos procedentes de la combustión de biomasa no han sido prácticamente estudiados para su aplicación en hormigones convencionales y la conjunción de éstos con áridos reciclados en la fabricación de hormigones no estructurales no ha sido estudiada. Por lo tanto, parece interesante la investigación de ambos para estudiar el comportamiento de hormigones fabricados con los mismos y sus posibilidades reales de aplicación de obra.

# CAPÍTULO IV

## *OBJETIVOS*

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## *OBJETIVOS*

Los ARH y ARM han sido estudiados en el pasado para su uso en hormigones reciclados. Sin embargo, la reducción de la calidad de los hormigones resultantes hace necesario estudiar la posibilidad de optimización de estos áridos reciclados para contrarrestar la pérdida de calidad. Por otro lado, la posible utilización de las CFB resultantes de la combustión de biomasa para producción de energía, en hormigones reciclados, no ha sido prácticamente investigada.

Por ello, esta investigación tiene como objetivo principal "*la implementación y optimización de cenizas de fondo de biomasa y áridos reciclados en hormigones no estructurales mediante el análisis de sus propiedades mecánicas y de durabilidad, así como su posible impacto ambiental* ".

Para tal fin, este objetivo general está desglosado en cuatro objetivos parciales:

**1.-** Evaluar la capacidad cementante de las CFB. Se pretende para ello realizar un análisis de las propiedades físico-mecánicas de un mortero fabricado con CFB y comparar los resultados atendiendo a variables como la sustitución por cemento o arena por CFB, la tasa de sustitución, y el tipo de cemento.

1.1.-Estudiar mediante ensayos la densidad y porosidad de morteros fabricados con CFB y comparar dichos resultados con el mortero de control para evaluar la diferencia obtenida.

1.2.-Comparar los valores de resistencia a compresión y flexión de los morteros fabricados con CFB con el mortero de referencia, obtenidos a diferentes edades. Con ello se pretende evaluar la capacidad cementante de las CFB.

1.3.-Estudiar mediante observación al microscopio la porosidad de los morteros con contenido en CFB respecto del control para determinar si existen diferencias signficativas.

**2.-** Estudiar la viabilidad de compensar las pérdidas en el comportamiento mecánico del hormigón de referencia mediante la adición de cemento. Se estudiarán para ello, tanto las propiedades mecánicas como las de durabilidad de hormigones fabricados con áridos reciclados con diferentes cantidades de cemento.

2.1.-Obtener similares valores de resistencia a compresión en los hormigones fabricados con ARH respecto del control mediante la adición de cemento para compensar las posibles pérdidas de resistencia.

2.2.-Analizar el comportamiento mecánico y de durabilidad de hormigones de acuerdo a la aplicación diferentes tasas de incorporación de ARH y a la adición de diferentes tasas de cemento.

2.3.-Observar el comportamiento de los ARH en hormigones similares con diferente tipo de cemento para determinar bajo qué tipo de cemento es más idónea su aplicación.

**3.-** Estudiar las posibilidades de aplicación de hormigones fabricados con una mezcla de AR y CFB. Para ello, se analizará la influencia de las cenizas de fondo de biomasa, como fracción fina, en el comportamiento mecánico y de durabilidad en hormigones fabricados con áridos reciclados gruesos.

3.1.-Analizar el comportamiento mecánico y de durabilidad de hormigones fabricados con CFB como sustituto de la AN, respecto del hormigón de control.

3.2.-Estudiar el comportamiento mecánico y de durabilidad de hormigones fabricados con ARH y ARM respecto del hormigón de referencia.

3.3.-Fabricar hormigones con CFB y ARH/ARM y determinar sus propiedades mecánicas y de durabilidad para evaluar sus posibilidades de aplicación en hormigones no estructurales.

**4.-**Analizar la influencia de cenizas de fondo procesadas mediante la extracción de sus partículas flotantes en hormigones fabricados con incorporaciones de áridos reciclados tanto en su fracción gruesa como en su fracción fina. Para tal fin, se realizarán ensayos para estudiar de comportamiento mecánico y de durabilidad y se realizará un análisis de las variables respecto a los datos obtenidos.

4.1-Fabricar hormigones con diferentes tasas de sustitución de AN por CFB sin procesar y procesadas (con extracción de partículas flotantes) y evaluar las diferencias obtenidas entre ellos.

4.2.-Evaluar el comportamiento mecánico y de durabilidad de hormigones fabricados con altas tasas de sustitución de AN por CFB (hasta un 30% en volumen).

4.2.-Analizar el comportamiento mecánico y de durabilidad de hormigones fabricados con ARH y ARM "todo-uno" mediante la sustitución de áridos naturales en toda su fracción granulométrica.

# CAPÍTULO V

## *METODOLOGÍA*

# CAPÍTULO V

## *METODOLOGÍA*

Para conseguir los cuatro objetivos marcados en el apartado anterior, esta Tesis Doctoral se ha dividido en cuatro fases:

**- Fase 1. Determinación de la capacidad cementante de cenizas de fondo de biomasa.**

En esta fase, se realizó un estudio del comportamiento mecánico de morteros fabricados con CFB para evaluar su capacidad cementante y su comportamiento como árido fino en morteros de albañilería.

Para estudiar su capacidad cementante, diferentes porcentajes y diferentes tipos de cemento (0, 10 y 20%, en volumen, de cemento CEM-I y CEM-II) se sustituyeron por cenizas de fondo de biomasa trituradas.

Para estudiar la viabilidad de uso de las cenizas de fondo de biomasa como fracción fina, se aplicaron sustituciones de 0, 10 y 20%, en volumen, de AN normalizada según UNE-EN 196-1 por cenizas de fondo de biomasa en su fracción 0-2 mm.

Se estudió su comportamiento mecánico a través de los ensayos de consistencia, porosidad y densidad a 28 días y resistencia a flexión y compresión.

Los resultados obtenidos se muestran en el trabajo marcado como "Publicación 1", publicado en una revista científica del primer cuartil.

De forma paralela, se estudió la mejora de propiedades mecánicas de las cenizas de fondo de biomasa a través de la calcinación de éstas, para asegurar una baja proporción de materia orgánica. Dicho trabajo fue presentado en un congreso internacional, cuya transcripción se adjunta como Aportación 3 del Anexo I.

**-Fase 2. Análisis del efecto de adición de cemento en las propiedades mecánicas y de durabilidad de hormigones fabricados con áridos reciclados de hormigón**

Por otro lado, se investigó la influencia de la cantidad de cemento, con dos relaciones agua/cemento diferentes, en las propiedades mecánicas y de durabilidad de hormigones fabricados con diferentes tasas de sustitución de grava natural por ARH.

Con tal fin se realizaron dos series de cuatro amasadas de hormigón de acuerdo a una cantidad base de cemento (300 kg y 375 kg). Con el objetivo de obtener semejantes valores de resistencia a compresión a 28 días como valor constante, se adicionó un 3, 6 y 12% en cada serie para tasas de sustitución de 20, 50 y 100% de grava natural por ARH.

Además de la resistencia a compresión, se realizaron otros ensayos de propiedades físico-mecánicas como resistencia a flexión, módulo de elasticidad, densidad y absorción, absorción de agua al vacío y UPV. Asimismo, se realizaron ensayos de durabilidad tal y como penetración de agua bajo presión, penetración de cloruros y retracción del hormigón.

Los resultados obtenidos en esta segunda fase, se publicaron en una revista científica, tal y como se puede comprobar en la Publicación 2.

Previo a la realización de esta investigación, se realizó un estudio para analizar el comportamiento mecánico y de durabilidad de hormigones con áridos naturales y con sustituciones de CFB (Aportación 2 del Anexo I).

Adicionalmente se realizó un estudio de impacto ambiental para analizar el grado de lixiviación de bloques de cada amasada de hormigón fabricada, cuyos resultados se recogen en la Publicación 3 del Anexo I.

**- Fase 3. Estudio de las propiedades mecánicas y de durabilidad en hormigones fabricados con áridos reciclados y cenizas de fondo de biomasa.**

La Fase 3 enlazó la Fase 1 y Fase 2 mediante la fabricación de hormigones con sustituciones de AN por CFB en su fracción fina y sustituciones de grava natural por ARH y ARM en su fracción gruesa.

Para el diseño de la investigación se tuvieron en cuenta los resultados obtenidos en las anteriores fases. Del análisis de la Fase 1 se determinó el tipo de cemento (CEM-I) por su mejor comportamiento en conjunción con las cenizas de fondo de biomasa.

Además, se eligió el tipo de sustitución de AN por CFB por ser más óptima dicha sustitución que la del cemento. Por otro lado, del análisis de la Fase 2 se determinó la cantidad de cemento (300 kg) por obtenerse resistencias a compresión más acordes al tipo de uso de hormigones fabricados con áridos reciclados (hormigones en masa con baja resistencia característica) y se mantuvo la cantidad de 300 kg de cemento por ser el valor de referencia para el hormigón de referencia.

La investigación de la Fase 3 se centró en el análisis de las propiedades físico-mecánicas y de durabilidad de 3 series de amasadas clasificadas en función de su árido grueso. La primera serie contuvo hormigones fabricados con grava natural, mientras que las series 2 y 3 se realizaron con áridos reciclados gruesos de hormigón y mixtos respectivamente.

Como variable en cada amasada se aplicaron tres tasas de sustitución de AN por cenizas de fondo de biomasa (0, 3 y 6% en volumen). Las propiedades físico mecánicas fueron resistencia a compresión, resistencia a flexión, densidad y absorción. Por otro lado, las propiedades de durabilidad analizadas fuero penetración de agua bajo presión, penetración de cloruros y retracción del hormigón.

Como en las fases anteriores, tras la recopilación de datos se procedió al análisis de los mimos, publicándose el trabajo realizado en la Publicación 3.

**- Fase 4. Determinación de la influencia de cenizas de fondo de biomasa procesadas y áridos reciclados "todo-uno" en hormigones.**

La Fase 4 dio un paso más en el estudio de hormigones con sustituciones de áridos naturales por CFB y AR, tanto de hormigón como mixtos. Para este estudio se aplicaron dos innovaciones fundamentales respecto del estudio anterior. La primera concernió a la aplicación de las cenizas de fondo de biomasa, que fueron aplicadas tanto de forma tradicional como procesadas (con extracción de partículas flotantes). La segunda innovación fue la incorporación de áridos reciclados de granulometría continua, es decir, la sustitución de áridos naturales por áridos reciclados en toda su fracción granulométrica.

Por tanto, se realizaron tres series de amasadas clasificadas de acuerdo al tipo de árido aplicado (0, 15 y 30% de ARH y ARM en volumen). Cada serie estuvo compuesta de 5 amasadas, de acuerdo al porcentaje de sustitución de AN por CFB (0% de CFB, 15-30% de CFB sin procesar y 15-30% de cenizas de CFB procesadas, en volumen).

Se estudiaron tanto propiedades mecánicas (densidad y absorción, resistencia a compresión, resistencia a flexión y velocidad de impulsos ultrasónicos) como propiedades de durabilidad (penetración de agua bajo presión, difusión del ion cloruro y retracción del hormigón).

Los resultados obtenidos fueron publicados en una revista del JCR y se exponen en la Publicación 4.

A continuación, se muestra un esquema con estas cuatro fases y como se interrelacionan entre ellas (**Figura 5.1**):

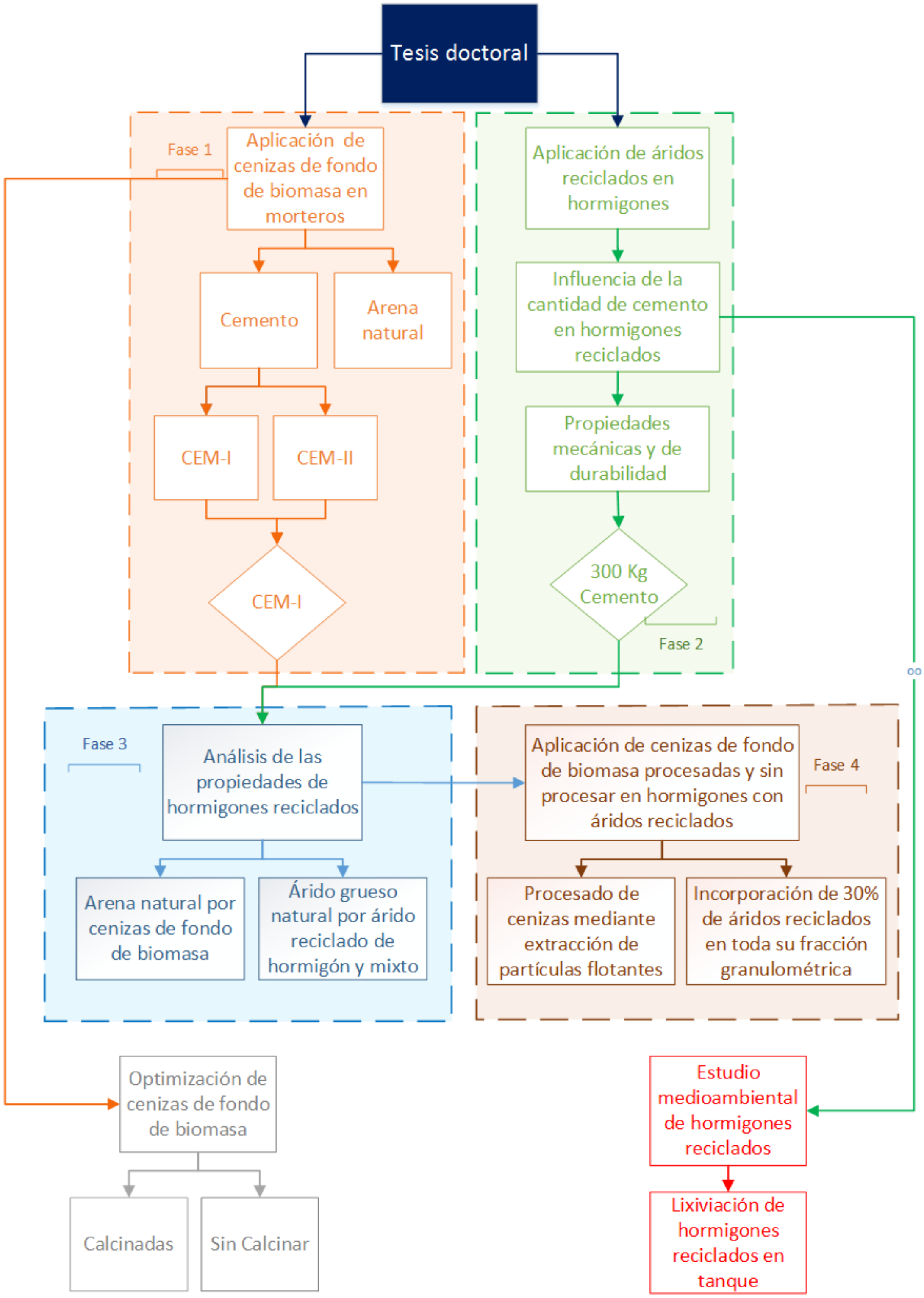


**Figura 5.1.** Fases de la metodología aplicada

# CAPÍTULO VI

*COMPENDIO DE PUBLICACIONES INDEXADAS*

# CAPÍTULO VI

## *COMPENDIO DE PUBLICACIONES INDEXADAS*

El desarrollo de las cuatro fases definidas en la metodología da como resultado cuatro publicaciones en revistas indexadas, las cuales se exponen transcritas a continuación.

### PUBLICACIÓN 1. MECHANICAL PERFORMANCE OF BEDDING MORTARS MADE WITH OLIVE BIOMASS BOTTOM ASH

La Fase 1 de la metodología aplicada para esta Tesis Doctoral dio como resultado una publicación en una revista indexada en JCR, tal y como se expone a continuación.

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## Mechanical performance of bedding mortars made with olive biomass bottom ash

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## *Abstract*

Two waste streams result from biomass combustion for power generation: biomass fly ash (BFA), which is used as fertilizer in agriculture, and biomass bottom ash (BBA) currently with no practical applications and generally deposited in landfills.

This study provides significant information about the mechanical behaviour of mortars made with BBA, and the influence of several variables on such behaviour, namely type of cement, cement content, BBA incorporation ratio, and material type replaced with BBA.

Two mortar families were produced according to the type of cement applied (CEM-I and CEM-II). In each family, three volumetric replacement ratios of natural sand (NS) with BBA (0%, 10% and 20%) and three cement contents (515 g/L, 485 g/L and 450 g/L) were used. Mortars with replacement of cement with BBA (10% and 20% in cement volume) were also produced.

Four mechanical properties were analysed: porosity, density, flexural strength and compressive strength. Strength was analysed at different ages to assess its evolution over time.

There was a declining trend with the application of BBA for all properties analysed. Different behaviours were observed depending on the type of cement used or the material type replaced with BBA. Furthermore, there is an influence of porosity and density on strength due to the high absorption of BBA, allowing establishing meaningful relationships between the properties analysed.

This paper proves the viability of bedding mortars with BBA depending on the cement type and content and the BBA incorporation ratio.

## *Keywords*

Biomass bottom ash, bedding mortars, mechanical behaviour, cement content

## *Acronyms*

ASR - alkali silica reaction; BFA - biomass fly ash; BBA - biomass bottom ash; EHE-08 - Spanish concrete code; NS - natural sand; OPC - ordinary Portland cement; P - plasticizer; PG-3 - Spanish technical specification for road and bridge works; SSD - saturated surface dry.

## *Introduction*

The generation of renewable energy has significantly increased in recent years, primarily due to the need to reduce gas emissions harmful to the environment. In 2010, the *per capita* emission of $CO_2$ was 5.8 metric tonnes in Spain, whereas in the Euro area, it was 7.4 metric tonnes *[1].* According to the International Agency Energy, the current trend to reduce $CO_2$ emissions involves increasing the use of renewable energy as a substitute of energy from fossil fuels. Its use favoured the generation of 370 TWh worldwide, corresponding to 1.5% of global electricity generation *[2]*. According to the European Directive 2009/28/CE

[3], it is expected that the amount of renewable energy consumed will become 20% of the total by the year 2020. This has led to an increase of the number of renewable energy power plants in Spain. In the region of Andalusia alone, there are 17 power plants using biomass combustion. This biomass is mainly composed of pruning from olive trees and other varieties of vegetation, such as poplar and eucalyptus trees.

Generating power from this type of raw material through combustion produces two waste products, biomass fly ash (BFA), formed by light particles agglomerated in the upper combustion furnace, and biomass bottom ash (BBA), consisting of heavier particles deposited at the base of the furnace.

Both waste products are formed by particles that are not combusted during the process *[4]*. BFA has been widely used in agriculture, mainly as fertilizer *[5].* Some investigations on its use in construction have been performed. *Rajamma et al. [6]* studied the characterisation and use of BFA in cement-based materials by replacing Ordinary Portland Cement (OPC) with BFA at various ratios (10%, 20% and 30% in cement mass). They measured various properties of fresh and hardened mortars and concluded that replacing up to 20% of cement with BFA allows obtaining suitable mechanical strength. *Cuenca et al. [7]* manufactured self-compacting concrete using BFA from olive tree pruning combustion as filler, obtaining similar compressive strength in mixes with high amounts of superplasticisers relative to a reference concrete.

*Wang [8]* studied the influence of BFA on the compressive strength and alkali silica reaction (ASR) expansion in mortars. The author concluded that, for up to 25% incorporation by mass of BFA, ASR expansion decreased and compressive strength increased.

In Spain, an average of 43,000 Tn of BBA are generated each year. Despite the high production of BBA [9]. few investigations were conducted to study the possibility of using BBA in the construction sector. *Cabrera et al. [10]* made a physicochemical characterization of 30 samples of three biomass combustion plants to compare the results with the specifications set by PG-3 for use in roads. *Beltrán et al. [11]* studied the mechanical and durability properties of concrete manufactured with coarse recycled aggregates (from masonry and concrete) as substitute of coarse natural aggregates and BBA as substitute of natural sand (NS) (volumetric NS/BBA replacement ratios of 0%, 10% and 20%). The results showed the feasibility of incorporating 10% of BBA in non-structural concrete.

*Modolo et al. [12]* investigated the influence of BBA on adhesive mortars, performing replacements of NS by BBA at rates of 25%, 50% and 100% in mass. The results proved the feasibility of using BBA in adhesive mortars within given limits.

*Maschio et al. [13]* replaced cement with BFA and BBA at 5%, 10%, 15%, 20% and 30% in mass, to study the rheological behaviour and compressive strength of mortars. It was concluded that up to 5% cement replacement with BBA, compressive strength and absorption were similar to those of the reference mortar.

The scarce literature shows the lack of information on the mechanical behaviour of mortars containing BBA. Therefore, the study of properties of mortars containing BBA provides significant data on the influence of BBA in the physical and mechanical behavior of bedding mortars. The knowledge of the properties of mortars with BBA allows defining a new way to applying BBA, thereby enabling an environmental output for this type of by-product in the construction sector.

Based on these premises, this work studies in detail the mechanical behaviour of mortars in function of four main variables: type of cement, cement content, BBA incorporation ratio, and material replaced with BBA, providing interesting and novel results on the implementation of BBA in bedding mortars.

The results showed a reduction of compressive and flexural strength with the incorporation of BBA as replacement of cement and sand, as expected *[13-14]*. Similarly, due to the high porosity of BBA, mortars with lower density and higher porosity, relative to the control mortar, were obtained in all cases. On the other hand, interesting results were obtained by analysing the influence of given parameters on the mechanical behaviour and defining trends and relationships between various properties.

## *Materials*

### *Natural Sand and Biomass Bottom Ash*

Natural sand (NS), with nominal particle sizes of 0-2 mm, was used as reference aggregate in the production of mortars. The characteristics of this type of sand comply with Standard DIN EN 196-1, and its main properties are shown in Table 1.

Biomass bottom ash (BBA) with nominal particle sizes of 0-2 mm from a thermal plant located in Linares, Jaen (Spain) was used to replace cement and NS. This BBA is the result of the combustion of waste from olive pruning and other plant compounds. The plant material is deposited in a chamber and burned at 403 °C to generate steam that flows through a closed-loop system. BBA is the non-combusted waste generated in the process. Its physical and mechanical properties are presented in Table 1.

**Table 1.** NS properties characterisation

| | Standard | BBA | EHE-08 limits |
|---|---|---|---|
| Apparent density (kg/dm$^3$) | UNE-EN 1097-6 | 2.18 | - |
| Dry density (kg/dm$^3$) | UNE-EN 1097-6 | 1.37 | - |
| SSD density (kg/dm$^3$) | UNE-EN 1097-6 | 1.67 | - |
| Absorption (%) | UNE-EN 1097-6 | 19 | 5% |
| Abrasion ratio (%) | UNE-EN 83115 | 29 | 40 |
| Acid-soluble sulphates (%$SO_3$) | UNE-EN 1744-1 | 0.26 | 0.8 |
| Water-soluble sulphates (%$SO_3$) | UNE-EN 1744-1 | 0.27 | 0.8% |
| Organic matter (%) | UNE-EN 1744-1 | 5.26 | 1% |

Table 1 shows that the absorption of BBA (19%) was significantly higher than that of NS (0.5%). Furthermore, the densities of BBA were lower than those of NS due to the high porosity of BBA. Similar values were obtained by *Cabrera et al. [10]*, who obtained an average absorption of 20% and a similar SSD density (1.7 kg/dm$^3$) for BBA from the same plant.

**Table 2.** BBA properties characterization

| | Standard | BBA | | EHE-08 limits |
|---|---|---|---|---|
| Apparent density (kg/dm$^3$) | UNE-EN 1097-6 | 2.18 | | - |
| Dry density (kg/dm$^3$) | UNE-EN 1097-6 | 1.37 | | - |
| SSD density (kg/dm$^3$) | UNE-EN 1097-6 | 1.67 | | - |
| Absorption (%) | UNE-EN 1097-6 | 19 | | 5% |
| Abrasion ratio (%) | UNE-EN 83115 | 29 | | 40 |
| Acid-soluble sulphates (%$SO_3$) | UNE-EN 1744-1 | 0.26 | | 0.8 |
| Water-soluble sulphates (%$SO_3$) | UNE-EN 1744-1 | 0.27 | | 0.80 |
| Organic matter (%) | UNE-EN 1744-1 | 5.26 | | 1 |
| Dissolved organic carbon (mg/l) | DIN EN 1484 | 730 | | - |
| Phenox index (mg(l) | DIN 38409-H16-1 | 0.34 | | - |
| Elemental content (wt.%) | UNE 80 215:1988 | Si | 24.52 | - |
| | | Ca | 14.12 | - |
| | | K | 13.10 | - |
| | | Mg | 2.38 | - |
| | | Al | 0.75 | - |
| | | Na | 0.38 | - |
| | | Ti | 0.14 | - |

The abrasion ratio of BBA was higher than that of NS, i.e. BBA is more susceptible to abrasion. However, the value obtained was below the maximum value (40%) indicated by the Spanish Concrete Code (EHE-08) *[15]*. This value is slightly higher than the average (26%) of the values obtained by *Vegas et al. (2009) [16]* for six fine recycled aggregates.

A chemical analysis of BBA concluded that it contains a high amount of organic matter (5.26%), as expected because the current combustion process does not eliminate this material. For complete removal of organic matter content, a new combustion process would be needed, with negative environmental impacts. This factor may affect the mechanical properties of mortars. Similar values were obtained by *Hinojosa et al. (2014) [17]* for samples of similar BBA.

Regarding size distribution, both NS and BBA were within the limits established by EHE-08 *[15]*. Furthermore, the analysis showed a continuous distribution of particle size for both fines, one of the steps necessary to ensure the compactness of mortars (Figure 1).

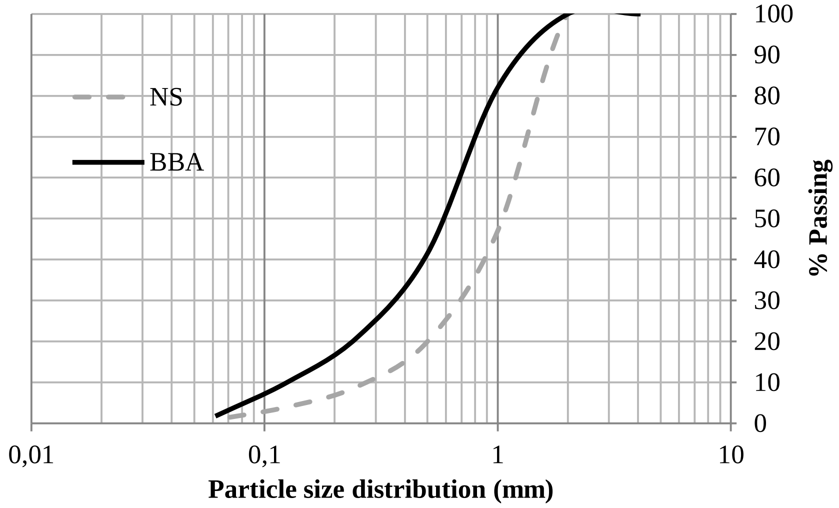



**Figure 1.** Particle size distribution

Respect to XRD-spectrum (Figure 2), the XRD analysis shows mainly Arcanite ($K_2SO_4$) and Calcite ($CaCO_3$); minor Quartz ($SiO_2$), Sylvite (KCl), Calcium Silicate ($Ca_2SiO_4$), Apatite ($Ca_5(F, OH)(PO_4)_3$); eventually Hydrocalumite (Ca-Al-Hydroxy-Carbonate-Hydrate) and Calcium Iron Oxide ($CaFeO_3$).

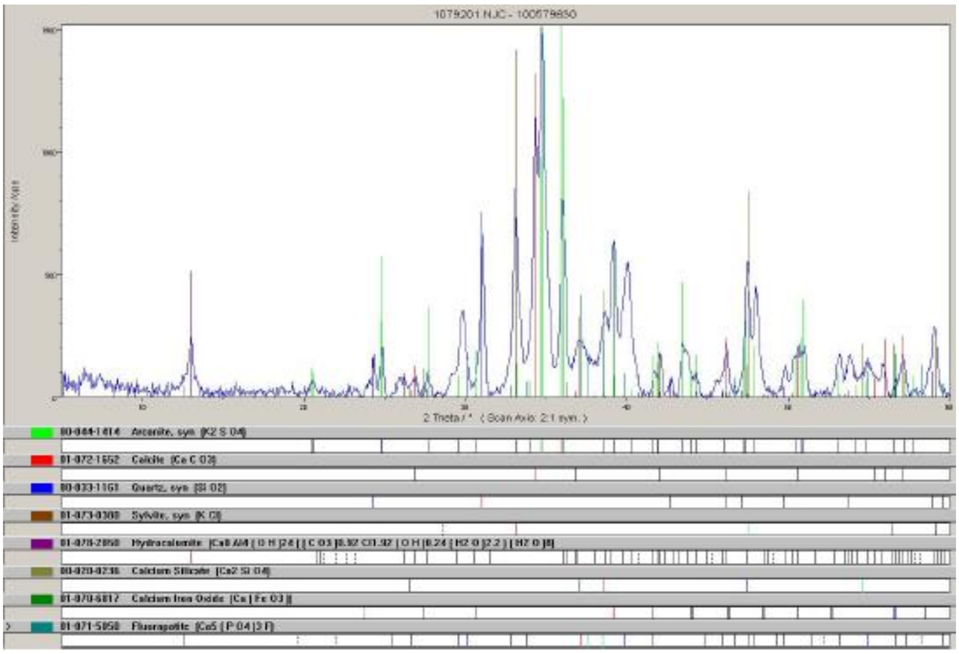



**Figure 2**. XRD spectrum

Two cements of different classes and characteristic strength were used in two mortar families to determine the influence of the type of cement on the mechanical properties of mortars made with BBA:

- Ordinary Portland Cement (OPC), composed primarily of clinker (> 95%), with high strength at 28 days (52.5 MPa) and normal curing at early ages. It is mainly used in high-strength concrete, concrete for aggressive environments due to its resistance to sulphates attack, and pre-stressed and precast concrete. Its commercial designation is CEM-I 52.5N/SR and its properties are shown in Table 3;

- Cement with additions, type CEM-II, with a high percentage of limestone-L filler (35%) and a strength of 32.5 MPa at 28 days. It is mainly used in mass concrete and concrete roads, soil stabilization and mortars. Its commercial name is CEM-II/B-L 32.5N and its properties are shown in Table 3.

**Table 3.** Properties of the cements used

| | $TiO_2$ | $Cl_2O_3$ | $Fe_2O_3$ | CaO | MgO | $O_3$ | $K_2O$ | $Na_2O$ | Size 45 μm | Size 32 μm | Blaine S. S. | LOI* | Density |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | % | % | % | % | % | % | % | % | % | $cm^2/g$ | % | $(kg/dm^3)$ |
| CEM-I | 0.18 | 4.14 | 4.51 | 63.75 | 0.91 | 3.24 | 0.75 | 0.31 | 6.2 | 16.1 | 3701 | 1.4 | 3.1 |
| CEM-II | 6.20 | 3.83 | 2.75 | 60.41 | 0.84 | 2.64 | 0.64 | 0.22 | 21.4 | 30.3 | 4524 | 1.92 | 3.1 |

### *Mixing water and compensation water*

The mixing water consisted of the water used to effectively hydrate the cement and compensation water took into account the high water absorption of BBA, thus allowing the same effective water/cement ratio in all mortars.

### *Water-reducing admixture*

To obtain similar consistencies in all mortars, a plasticizer (P) was used in the manufacture of mortars with BBA, at varying contents. The product used, called Neoplast, is a high-performance aerating plasticizer, with a density of 1,040 $g/cm^3$ and pH = 8. This avoids micro-cracking of the mortars by limiting the water content.

## *Mortars production*

### *Mixing procedure*

For proper mixing and production of the mortars, the guidelines of UNE-EN 196-1 were used. The mixing water, cement and admixture were inserted in the mixer and mixed for 30 sec. Then, the NS, BBA and compensation water were introduced in the mixer at low speed for 30 more sec. Finally, all of the materials were mixed at high speed (280 rev per min) for 30 more sec.

After mixing, the mortar consistency was tested using a shaking table according to standard UNE-EN 1015-3. Then the moulds were filled in layers and vibrated on the table. Finally, these moulds were stored in a chamber at 50% humidity and 20 ºC for 24 h. After that period, the moulds were immersed in a tank until testing.

### *Mortar mix proportions*

Two families of mortars were manufactured according to the cement type (CEM-I and CEM-II). In each family, three sets of mortars were made according to the cement content (515 g/L, 485 g/L and 450 g/L) (Figure 3).

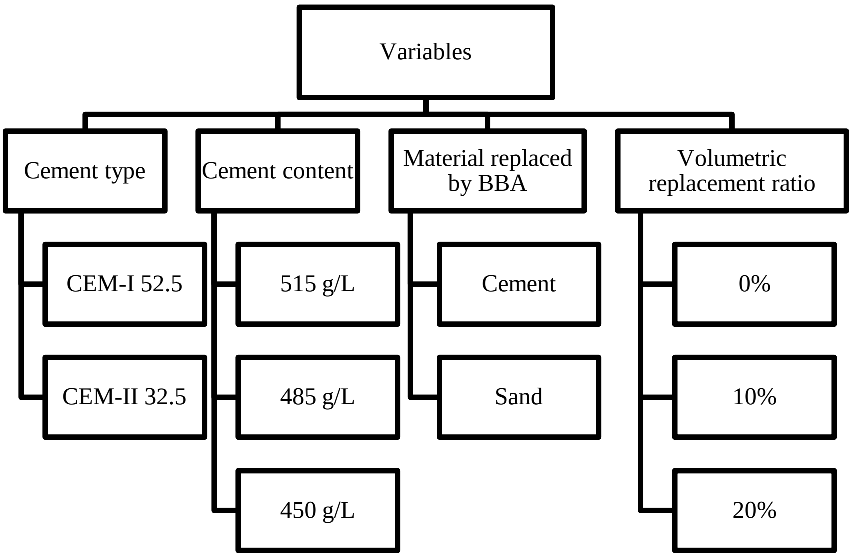



**Figure 3.** Mortars produced

Furthermore, two materials were replaced with BBA in mortars production (NS and CEM) in each series. For each one three volumetric replacement ratios were used (0%, 10% and 20%) (Table 4).

**Table 4.** Designation of the mortars produced

| | Cement content (g/L) | | BBA replacing NS | | BBA replacing CEM |
|---|---|---|---|---|---|
| CEM-I | 515 | A-I | A-I/ BB10 | A-I/BBA20 | A-I/BBA0-C = A-I |
| | 485 | B-I | B-I/ BA10 | B-I/BBA20 | B-I/BBA10-C |
| | 450 | C-I | C-I/ BBA10 | C-II/BBA20 | C-I/BBA20-C |
| CEM-II | 515 | A-II | A-II/ BB10 | A-II/ BBA20 | A-II/BBA0-C = A-II |
| | 485 | B-II | B-II/ BB10 | B-II/ BBA20 | B-II/BBA10-C |
| | 450 | C-II | C-II/ BB10 | C-II/ BBA20 | C-II/BBA20-C |

The mix proportions shown in Table 5 were used, al1 with an effective water/cement ratio (w/c) equal to 0.5. Mortars with replacement of cement with BBA (10% and 20% in cement volume) were also produced.

**Table 5.** Mix proportions of all mixes (g per litre)

| | Cement | NS | BBA | Water | Admixture | | Cement | NS | BBA | Water | Admixture |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A-I | 515 | 1541 | 0 | 258 | 0 | A-II | 515 | 1541 | 0 | 258 | 0 |
| A-I/BBA10 | 515 | 1387 | 79 | 258 | 1 | A-I/BBA10 | 515 | 1387 | 79 | 258 | 1.1 |
| A-I/BBA20 | 515 | 1233 | 158 | 258 | 1.6 | A-II/BBA20 | 515 | 1233 | 158 | 258 | 1.5 |
| B-I/ | 485 | 1605 | 0 | 243 | 0.2 | B-II/ | 485 | 1605 | 0 | 243 | 0.5 |
| B-I/BBA10 | 485 | 1444 | 82 | 243 | 1.8 | B-II/BBA10 | 485 | 1444 | 82 | 243 | 2 |
| B-I/BBA20 | 485 | 1284 | 165 | 243 | 2.22 | B-II/BBA20 | 485 | 1284 | 165 | 243 | 2.6 |
| B-I/BBA10-C | 485 | 1541 | 32 | 243 | 0.4 | B-II/BBA10-C | 485 | 1541 | 32 | 243 | 0.7 |
| C-I/ | 450 | 1682 | 0 | 225 | 0.5 | C-II/ | 450 | 1682 | 0 | 225 | 1.5 |
| C-I/BBA10 | 450 | 1514 | 86 | 225 | 2.25 | C-II/BBA10 | 450 | 1514 | 86 | 225 | 3 |
| C-I/BBA20 | 450 | 1345 | 173 | 225 | 3 | C-II/BBA20 | 450 | 1345 | 173 | 225 | 3.5 |
| C-I/BBA20-C | 450 | 1541 | 72 | 225 | 0.6 | C-II/BBA20-C | 450 | 1541 | 72 | 225 | 0.9 |

To determine the mortars' properties, fifteen 40 x 40 x 160 mm prismatic specimens were manufactured for each mix.

*Methodology tested*

Several variables and physical properties were analysed in this research to determine the mechanical behaviour of mortars containing BBA.

*Consistency*

The consistency of fresh mortar was determined immediately after mixing. A shaking table was used according to UNE-EN 1015-3. Consistency was kept constant, in order to compare the mortars under equal circumstances, by changing the superplasticizer's content.

*Porosity*

Porosity was measured through the following procedure: the weight right after curing and the weight after 24 h in an oven at 105 °C were measured; porosity is the ratio between the loss of weight and the initial weight; the result is expressed as a percentage.

To check the internal porosity qualitatively, samples were analysed using a scanning electron microscope.

*Density*

The dry density of the hardened mortar was determined at 28 days according to UNE-EN 1015-10.

*Compressive and flexural strengths*

The compressive and flexural strengths were measured at different ages (1, 7, 28 and 90 days) according to UNE-EN 196-1. A hydraulic press was used to apply a load at a constant speed.

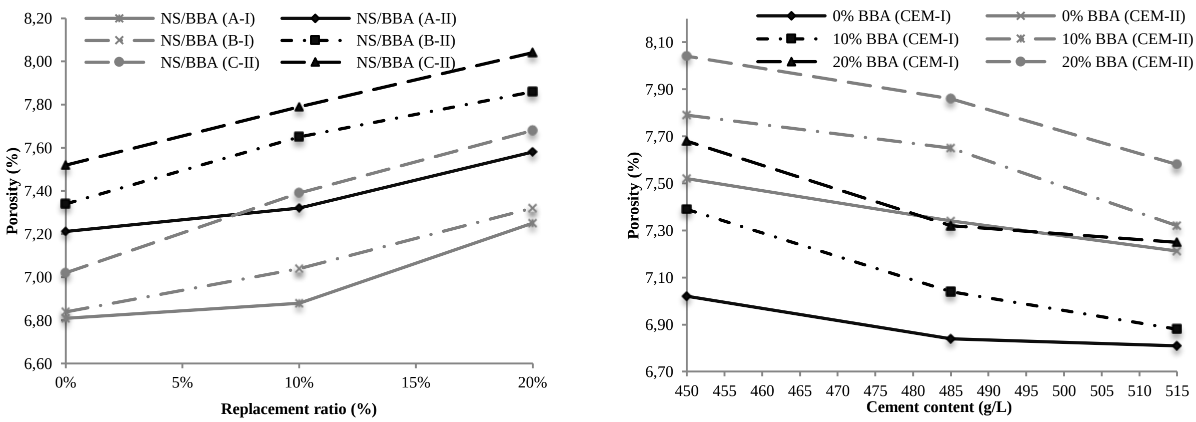
## *Results and discussion*

### *Consistency*

Table 6 shows the consistency values of the mortars. As intended, the values were all within the range 220 mm ± 2 mm. The superplasticizer content was therefore fine-tuned in preliminary studies to reach this target consistency.

### *Porosity*

The porosity was always higher in CEM-II mixes than in CEM-I mixes (Table 6), as expected due to the incorporation of limestone filler *[18]*. Furthermore, porosity increased when the cement content decreased, both in CEM-I and CEM-II mixes (Figure 4).




*a) Versus replacement ratio* *b) Versus cement content*

**Figure 4.** Porosity of mortars.

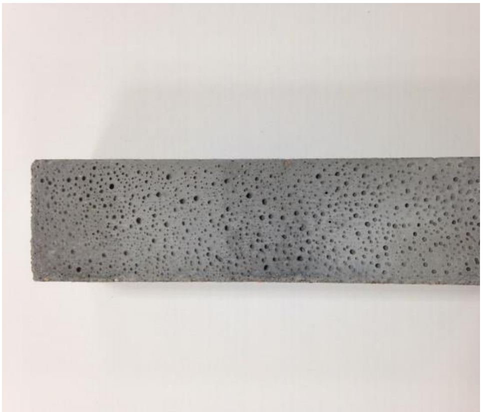
Porosity was lower when replacing CEM with BBA than when replacing NS with BBA. On the other hand, and as expected, porosity progressively increased when these materials were replaced with BBA, due to the high absorption of BBA (19%). This indicates that porosity is more susceptible to the BBA content than to the type of material replaced.

This is consistent with other authors' results. *Maschio et al. [13]* found that increasing by more than 5% the FBA and BBA content increased mortars' porosity. *Beltrán et al [10]* obtained increases in the porosity of concrete made with BBA relative to a control concrete without BBA.

The increase in porosity is related to a decrease in density and compressive strength *[15-16]*.

The difference in surface porosity between two types of mortars (A-I and A-IBBA20) is shown in Figure 5. A-I/BBA had higher number of surface pores than A-I due to the presence of BBA. Similar qualitative results were observed in the other mortars with BBA.

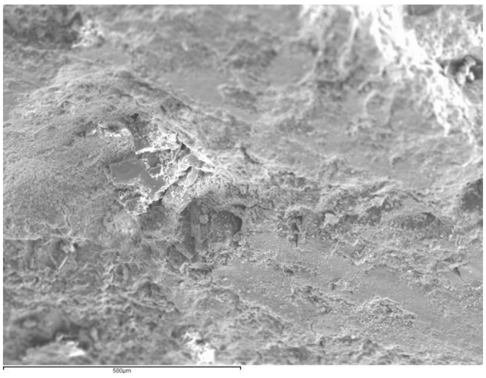
*a) Reference mortar (A-I)*



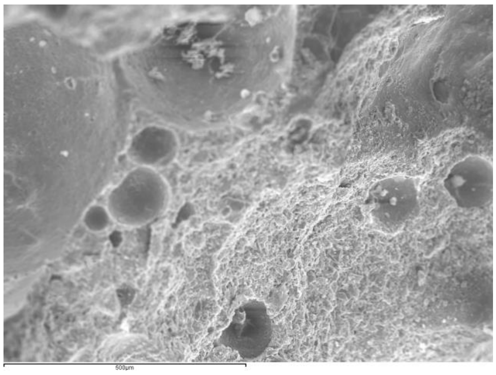
*b) Mortar with BBA (A-I/BBA20)*

**Figure 5.** Porosity surface

Also to study the porosity, an analysis was performed using a scanning electron microscope (Figure 6). The control mortar had fewer pores and a smaller pore size than the A-I/BBA20 mortar.



*a) Reference mortar (A-I)*



*b) Mortar with BBA (A-I/BBA20)*

**Figure 6.** Samples analysed by scanning electron microscopy. Scale: 500 μm

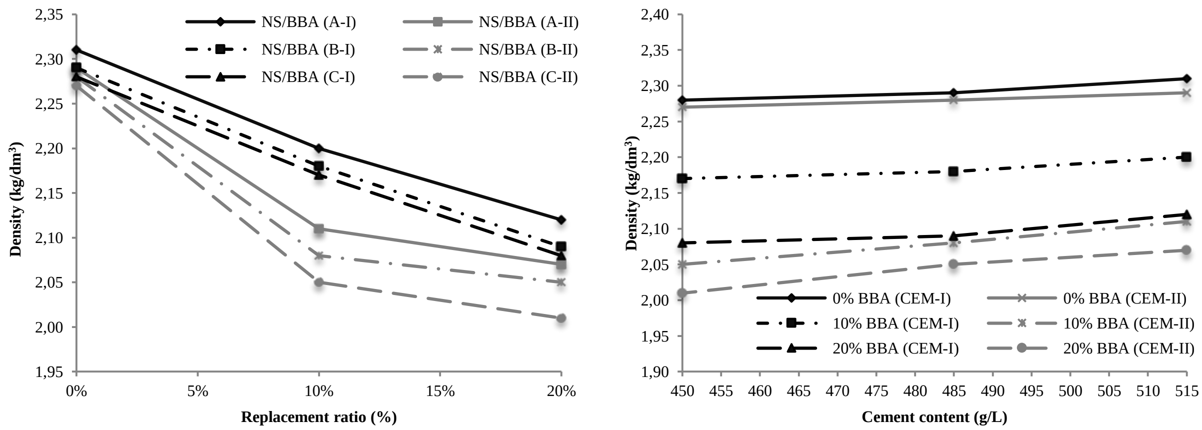
**Table 6.** Summary of the mortars test results

| | Consistency (mm) | Flexural strength (MPa) | | | | Compressive strength (MPa) | | | | Density (kg/dm³) | Porosity (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Age (days) | | 1 | 7 | 28 | 90 | 1 | 7 | 28 | 90 | 28 | 28 |
| A-I | 220 | 7.21 | 9.35 | 11.73 | 12.25 | 27.83 | 51.22 | 58.26 | 60.12 | 2.31 | 6.81 |
| A-I/BBA10 | 218 | 6.24 | 7.35 | 9.46 | 9.82 | 24.91 | 41.50 | 49.95 | 52.12 | 2.2 | 6.88 |
| A-I/BBA20 | 222 | 4.97 | 7.30 | 8.91 | 9.56 | 21.20 | 36.65 | 43.59 | 45.25 | 2.12 | 7.25 |
| B-I | 221 | 7.14 | 9.28 | 10.26 | 11.12 | 26.26 | 50.50 | 54.89 | 57.25 | 2.29 | 6.84 |
| B-I/BBA10 | 222 | 5.87 | 8.65 | 9.03 | 9.60 | 21.98 | 36.42 | 46.37 | 48.47 | 2.18 | 7.04 |
| B-I/BBA20 | 218 | 4.38 | 8.18 | 8.74 | 9.41 | 19.24 | 31.32 | 37.96 | 39.98 | 2.09 | 7.32 |
| B-I/BBA10-C | 218 | 6.84 | 8.94 | 9.69 | 10.50 | 22.72 | 40.74 | 52.06 | 54.14 | 2.28 | 6.96 |
| C-I | 220 | 5.72 | 8.90 | 9.64 | 10.36 | 24.41 | 47.39 | 50.74 | 52.44 | 2.28 | 7.02 |
| C-I/BBA10 | 220 | 5.07 | 7.99 | 8.88 | 9.17 | 18.70 | 34.17 | 43.01 | 45.85 | 2.17 | 7.39 |
| C-I/BBA20 | 219 | 5.41 | 7.79 | 7.89 | 8.73 | 18.19 | 28.90 | 37.90 | 40.25 | 2.08 | 7.68 |
| C-I/BBA20-C | 218 | 5.65 | 8.47 | 9.31 | 9.79 | 21.02 | 41.89 | 45.54 | 47.69 | 2.27 | 7.18 |
| A-II | 221 | 5.45 | 8.83 | 9.65 | 10.14 | 18.25 | 38.75 | 46.45 | 51.04 | 2.29 | 7.21 |
| A-II/BBA10 | 221 | 3.37 | 6.29 | 6.65 | 6.96 | 8.91 | 22.89 | 27.03 | 29.41 | 2.11 | 7.32 |
| A-II/BBA20 | 222 | 3.37 | 5.63 | 5.88 | 6.34 | 8.69 | 17.56 | 21.57 | 22.84 | 2.07 | 7.58 |
| B-II | 218 | 4.75 | 7.89 | 8.40 | 8.61 | 15.64 | 35.98 | 41.25 | 44.84 | 2.28 | 7.34 |
| B-II/BBA10 | 219 | 2.64 | 5.22 | 6.75 | 6.84 | 7.90 | 19.83 | 26.69 | 28.42 | 2.08 | 7.65 |
| B-II/BBA20 | 221 | 3.06 | 5.13 | 5.48 | 5.98 | 7.10 | 17.48 | 18.07 | 21.15 | 2.05 | 7.86 |
| B-II/BBA10-C | 220 | 3.95 | 7.65 | 8.25 | 8.41 | 12.64 | 33.69 | 40.11 | 43.84 | 2.25 | 7.48 |
| C-II | 222 | 3.50 | 5.65 | 6.75 | 6.98 | 12.25 | 24.87 | 32.79 | 34.80 | 2.26 | 7.52 |
| C-II/BBA10 | 219 | 2.75 | 5.22 | 6.05 | 6.04 | 8.46 | 17.72 | 23.55 | 27.42 | 2.05 | 7.79 |
| C-II/BBA20 | 220 | 2.57 | 4.34 | 4.40 | 4.60 | 6.49 | 14.20 | 18.33 | 19.66 | 2.01 | 8.04 |
| C-II/BBA20-C | 219 | 3.41 | 5.41 | 6.25 | 6.74 | 10.98 | 23.47 | 29.74 | 32.98 | 2.23 | 7.72 |

### *Density of hardened mortar*

The density of hardened mortar was higher in mortars with CEM-I than in mortars with CEM-II, as expected, due to the lower density of the limestone filler relative to the clinker (Figure 7).

Furthermore, the mortars density gradually decreased as the cement content declined due to loss of compacity of the mortar. However, the reduction was not significant.




*a) Versus replacement ratio* *b) Versus cement content*

**Figure 7.** Density of mortars

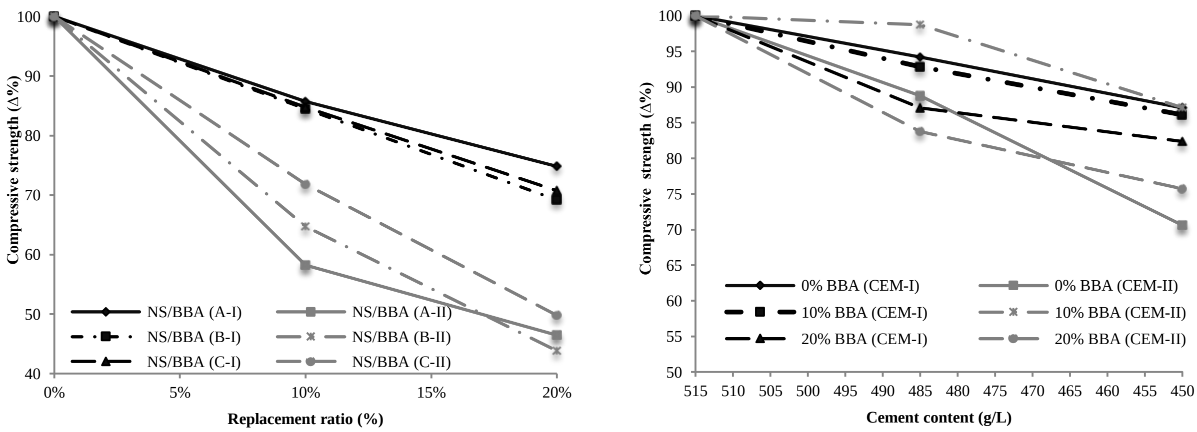
The replacement of materials with BBA reduced mortars density. However, as for porosity, the influence of BBA incorporation was more significant when replacing NS.

On the other hand, the density in both families progressively declined as the incorporation ratio of BBA increased, due to the lower density and higher organic matter content of BBA. However, the influence of the BBA content was higher in mortars with CEM-II, which could further affect the mechanical properties of these weaker mortars.

Based on these results, incorporating BBA always results in lower density and higher porosity in mortars, and the more so the higher the incorporation ratio. This finding is consistent with the results of other authors. *Cabrera et al. [10]* showed that BBA may crush under mechanical stress. *Carrasco et al. [21]* found density decreases and porosity increases in building blocks resulting from the incorporation of BBA (10-90% in mass).

***Compressive strength***

As expected, the compressive strength increased with curing time *[22-23]* for all series (Table 6). Also as expected, higher compressive strength values were obtained in CEM-I mortars than in CEM II mortars (Figure 8), due to the presence of limestone filler in CEM-II. Again as expected, the compressive strength goes down as the cement content decreases. Figure 9 shows the relationship between compressive strength and porosity, according to cement content.




*a) Versus replacement ratio* *b) Versus cement content*

**Figure 8.** Compressive strength of mortars at 28 days.

Mortars with replacements of CEM with BBA had higher compressive strengths than those with replacement of NS with BBA. The compressive strength gradually declined as the BBA incorporation ratio went up, in both CEM-I and

CEM-II families, due to BBA's higher porosity, which provides lower compacity to the hardened mortar.

Moreover, other factors may lead to a reduction in compressive strength, such as the high organic matter content present in BBA (5.26%), related with high water absorption *[24]*, and its high abrasion susceptibility (29%).

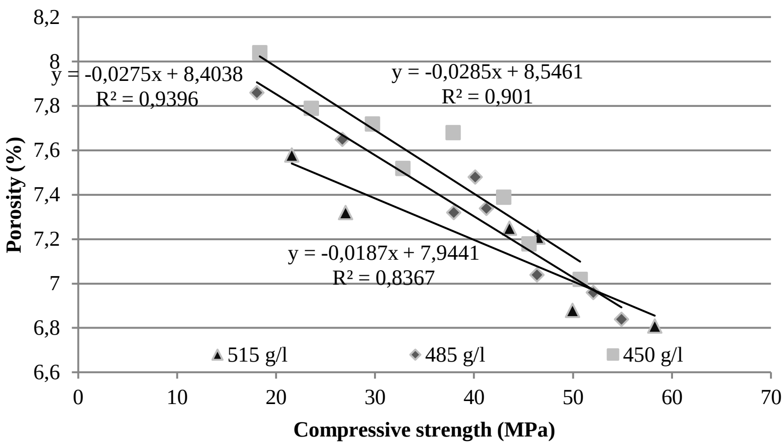



**Figure 9.** 28-day compressive strength versus porosity in terms of cement content.

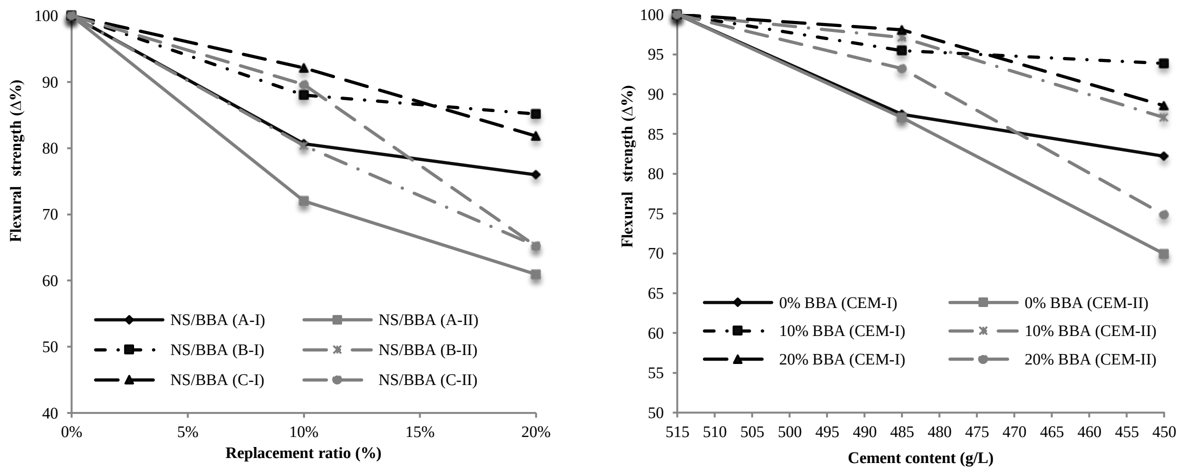
The reduction in compressive strength with increasing BBA content was more significant in mortars with CEM-II, due to their higher porosity and lower density compared to CEM-I mortars.

This finding is different from the results obtained by other researchers with other types of waste, where higher values of compressive and flexural strength were obtained relative to the reference mortar by replacing natural sand with recycled sand. *Lin et al. [25]* used replacement ratios of 0, 5, 10, 20 and 30% of cement with fly ash from the incineration of municipal solid waste and waste from the manufacture of LED lights in 5 x 5 x 5 cm samples, obtaining higher values of compressive strength than in the reference mortar. *Ledesma et al. [26]* applied different ratios of replacement of natural sand with fine recycled concrete aggregates (0, 5, 10 and 40%) obtained by crushing and sieving recycled concrete and using the 0-4 mm fraction. Higher compressive strength values were obtained than in the reference mortar.

However, the reduction in mechanical properties in our study was similar to that experienced by *Carrasco et al. [21]*, where the compressive strength decreased in building blocks incorporating BBA.

### *Flexural strength*

For all series and as expected, the flexural strength increased with curing age, as for compressive strength (Table 6). At 28 days (Figure 10), higher flexural strengths were obtained in CEM-I mortars than in CEM-II mortars due to the limestone filler in CEM-II. However, the influence of the cement type was lower for flexural strengths than for compressive strength.




*a) Versus replacement ratio* *b) Versus cement content*

**Figure 10.** Flexural strengths of mortars at 28 days

Again as expected, the flexural strength declined with the cement content, but this reduction was less significant in CEM-I mortars, as for compressive strength.

Regarding the replacement of materials by BBA, the flexural strength loss was lower for CEM with BBA replacement than for NS with BBA replacement.

Furthermore, for both families, the flexural strength decreased when replacing NS with BBA, and the more so the higher the replacement ratio. As for compressive strength, the decline in the flexural strength of mortars with BBA was due to the greater porosity and high organic matter content of BBA.

This is consistent with other authors' results. For example, *Rajamma et al. [24]* obtained a decrease in flexural strength as the replacement ratio of cement with BFA increased.

An excellent correlation was obtained between the compressive strength and flexural strength for all the mortars at all ages tested ($R^2$ = 0.96) (Figure 11). In general, the flexural strength was approximately 20% of the compressive strength in all mixes.

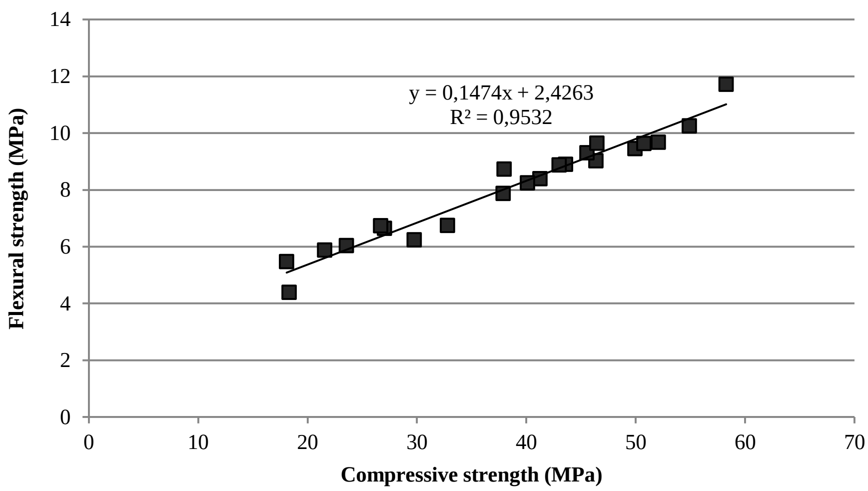



**Figure 11**. Flexural strength versus compressive strength at 28 days

## *Conclusions*

According to the results and evaluation made, incorporating BBA provided no improvements on the mechanical properties of the manufactured bedding mortars due to the high values of porosity and organic matter content of BBA.

However, the influence of BBA on CEM-I mortars was less pronounced than in CEM-II mortars. This may be due to the reduced performance in terms of the interaction between the limestone filler in CEM-II and BBA.

In spite of the reduction of mechanical properties resulting from the incorporation of BBA, this specific waste can be used in all types of bedding mortars, even though it is more specifically suitable for mortars type M and N, according to ASTM C 270.

Therefore, even the mortar with higher replacement ratio of NS with BBA (20% by volume) and 450 g of CEM-II, i.e. the one with the lower mechanical characteristics, can be applied as bedding mortar in walls and other building elements, complying with a minimum of 2500 psi (17.23 MPa) of compressive strength (according to ASTM C 270).

Furthermore, the results suggest the possibility of using higher replacement ratios and fewer cement content for both types of replacement and both types of cement used to achieve suitable (the minimum necessary for the mortar to be classified as type M or N) compressive strength for type M and N bedding mortars.

Nevertheless, it may be advisable to encourage BBA optimization processes, such as removing organic matter by improving the existing combustion process.

## *Standards used in the experimental work*

ASTM C 270: Standard specification for mortar for unit masonry.

UNE 83-115-89: Measurement of the friability coefficient of sand *(in Spanish).*

UNE-EN 1015-10: Methods of test for mortar for masonry. Part 10: Determination of dry bulk density of hardened mortar *(in Spanish).*

UNE-EN 1015-3: Methods of test for masonry mortars. Part 3: Determination of consistence of fresh mortar (by shaking table) *(in Spanish).*

UNE-EN 1097-6:2001/A1: Tests for mechanical and physical properties of aggregates; Part 6: Determination of density and water absorption of the particles *(in Spanish).*

UNE-EN 1744-1: Tests to determine the chemical properties of aggregates. Part 1: Chemical analysis *(in Spanish).*

UNE-EN 196-1: Methods of testing cements. Part 1: Determination of mechanical strength *(in Spanish).*

UNE-EN 933-1: Tests to determine the geometrical properties of aggregates. Part 1: Determination of particle size distribution *(in Spanish).*

## *Acknowledgements*

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i by and for the benefit of businesses (Technology Fund)", and the European Regional Development Fund (ERDF) within the INNPACTO 2011 programme. The support of the CERis-ICIST Research Institute, IST, University of Lisbon and of the FCT (Foundation for Science and Technology) is also acknowledged.

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# PUBLICACIÓN 2. EFFECT OF CEMENT ADDITION ON THE PROPERTIES OF RECYCLED CONCRETES TO REACH CONTROL CONCRETES STRENGTHS.

La segunda aportación, publicada en una revista indexada en el JCR, y correspondiente con la Fase 2 descrita en la metodología, se expone a continuación.

**Autores: M.G. Beltrán**, A. Barbudo, F. Agrela, A.P. Galvin, J.R. Jimenez.

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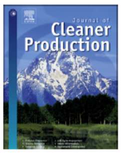


Effect of cement addition on the properties of recycled concretes to reach control concretes strengths

CrossMark

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## *Abstract*

Recycled aggregates from construction and demolition waste have previously been used to manufacture recycled concrete. Generally, these aggregates weaken the physical properties of concrete, such as the density, durability, compressive strength, flexural strength, water penetration, and chloride penetration. This is predominately attributed to the porosity of particles with adhered mortar or to ceramic particles. In other studies, cements with additions (fly ash, slag, silica fume...) were used to compensate for the effect of incorporation of recycled aggregates. In another, plasticizers were used to improve workability or mechanical properties of recycled concrete. However, the innovation of this research is the use of different amounts of cement according to replacement ratios of natural aggregates for recycled concrete aggregates to achieved structural concretes. Also, two different water/cement ratios were used to analyze if these reached compressive strength similar to control concrete manufactured with natural aggregates. The results revealed that a small increase in the volume of cement (12%) maintained the mechanical properties and reduced the loss of concrete durability. Therefore, increasing the amount of cement in recycled concretes is a feasible technique in works with low exposure to aggressive agents.

## *Keywords*

Concrete, compressive strength, mechanical properties, durability, recycled aggregates, cement.

## *Introduction*

In the last two decades, numerous researchers have studied the properties of recycled aggregates (RA) and their use as substitutes for natural aggregates (NA). According to *Agrela et al. (2011)*, RA contains adhered mortar or ceramic particles that increase the porosity of its particles. It results adversely affects material properties, such as density, water absorption and chemical and mechanical resistance *(Kwan et al., 2012).* Consequently, NA generally exhibit lower optimum moisture content and a higher maximum Proctor density than RA *(Barbudo et al., 2012).*

However, RA are a promising construction material with possible application as a sub-base for roads and embankments. *Jimenez et al. (2012)* evaluated the performance of RA in an experimental unpaved rural road built in Cordoba, Spain. Additionally, *Agrela et al. (2012)* used RA with cement as a sub-base in the construction of a highway access in Malaga, Spain.

RA have also been widely used in new concrete mixtures. *Maier and Durham (2012)* investigated the effect of recycled aggregates from concrete (RCA) and glass waste in fresh and hardened concrete, and *Mas et al. (2012*[a]*)* studied the effect of mixed recycled aggregates in non-structural concrete.

There are studies in which fine fractions of RA were used to manufacture new concrete. *Evangelista and Brito (2007)* substituted natural sand for fine RA in structural concrete and evaluated its mechanical behaviour, and *Pereira et al. (2012)* applied superplasticisers to limit the disadvantages associated with concrete incorporated with fine RA. However, coarse fractions of RA are more commonly used. *Bairagi et al. (1993)* conducted a study on the mechanical behaviour of concrete that was produced by varying the replacement ratio of NA with coarse RA and using various water/cement (w/c) ratios. *Tabsh and Abdelfatah (2009)* studied the mechanical properties of concrete that was produced with coarse RCA.

RA particles have a high porosity due to mortar adhered and, therefore, low densities. Consequently, new concretes that are manufactured with RA also have lower densities. This porosity also results in an increased demand for water and produces concrete with inferior mechanical properties, including a reduced compressive strength (*Gomez-Soberon*, 2002, obtained a loss of 12% for 100% replacement rate of NA by RCA), (*lower* flexural strength *(Topçu, 2004* obtained an average loss of flexural strength of 32%*)* and lower elastic modulus *(Katz, 2003* obtained a loss of elastic modulus up to 25%*;*). Some authors have recommended washing the aggregates to eliminate the finer fraction, which has more soluble sulphate content and greater water absorption *(Rodrigues et al., 2013).*

However, at replacement rates below 20 %, the compressive strength of concrete can be maintained *(Thomas et al., 2013).* Previous studies found differences in compressive strength between replacement ratios upper than 20 %. *Exteberría et al*. (2006) concluded concretes with 100% of recycled aggregates had a lower compressive strength compared to concrete control (20-25%), and *Kou et al. (2011)* studied compressive strengths of concretes with recycled aggregates were lower for all ages.

In fact, the Spanish Concrete Instruction *(EHE, 2008)* specifies the use of RA particles with sizes larger than 4 mm and replacement rates of up to 20 %, provided that the RA is obtained from crushed concrete and fulfils certain requirements.

However, compared to control concretes, the use of RCA has been shown to reduce concrete durability. *Mas et al. (2012)*[b] observed that the penetration of water under pressure increased with NA replacement ratio. A similar negative effect was observed for other durability properties, including dry shrinkage and chloride ion penetration. *Sanchez de Juan, (2009)* suggested that the adhered mortar contained in RA causes this reduction of durability.

Several investigations have been made to improve the properties of RA-containing concrete. *Kou et al. (2007)* recommended the addition of fly ash, *Pereira et al. (2012) and Barbudo et al. (2013*) proposed the use of superplasticisers, *Hwang et al. (2013)* advised the use of pozzolanic materials, and *Kou et al. (2011)* suggested the addition of silica fume or metakaolin. Other studies have applied several types of recycled aggregates for the manufacture of recycled concrete, as used tyre aggregates (*Bravo and Brito, 2012*), crushed glass aggregates (*Castro and Brito, 2013*), or marble wastes (*André et al., 2013*).

To maintain the desired concrete properties, the incorporation of recycled materials must adequately balance the replacement percentage.

For this, this study is focused on providing another alternative for obtaining properties similar to control concrete. Thus, the objective of this study is to investigate the behaviour of recycled concrete adding cement in amounts proportional to the replacement ratio of NA by RCA. To do this, two w/c ratios, from two different characteristic strengths, were selected that maintained the workability and compressive strength of control concrete made with natural aggregates. These w/c ratios were used to produce two series of concrete samples. To determine whether the addition of cement reinforced these properties, some mechanical and durability properties were measured and analysed.

## *Materials and methods*

### *Materials*

### *Cement*

Portland cement type 1 (OPC) with a characteristic strength of 42.5 MPa was used according to ASTM C150. This cement is a pure grey cement clinker that exhibits rapid hardening and is resistant to attack by sulphates. Its chemical properties are presented in Table 1.

**Table 1.** Chemical properties of cement

| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $K_2O$ | $Na_2O$ | Cl |
|---|---|---|---|---|---|---|---|---|
| 19.29 | 1.42 | 4.44 | 66.02 | 1.27 | 3.29 | 0.34 | 0.09 | 0.01 |

### *Recycled and natural aggregates*

The following aggregates were used in this research: a coarse *natural aggregate* (NA) with a nominal particle size of 4-16 mm (Figure 1), a *recycled concrete aggregate* (RCA) composed of crushed concrete blocks and mortar (>85%) from a treatment plant in Córdoba (Spain) with a nominal particle size of 4-20 mm (Figure 1), and *natural sand* (NS) particles ranging from 0-4 mm (Figure 1). The physical and chemical properties of these materials are presented in Table 2.

It is apparent from Table 2 that NA have the highest saturated surface dry density (SSD density) of the coarse aggregates. Because of the presence of adhered mortar, the RCA had a lower SSD density and higher absorption than the NA, as expected *(Farid Debied et al. 2010).*

**Table 2.** Physical and chemical properties of recycled and natural aggregates

| | | NA | RCA | NS |
|---|---|---|---|---|
| SSD density ($mg/m^3$) | EN-1097-6 | 2.68 | 2.38 | 2.53 |
| Absorption (%) | | 1.53 | 6.94 | 1.39 |
| Friability ratio (%) | EN-83-115 | - | - | 12 |
| Los Angeles coefficient (%) | EN-1097-2 | 20 | 29 | - |
| Sulphur content (%) | EN-1744-1 | <0.01 | 0.34 | <0.01 |
| Soluble sulphate (%$SO_3$) | EN-1744-1 | <0.01 | 0.86 | <0.01 |
| Chlorides (%) | EN-1744-1 | 0.1 | 0.03 | <0.01 |
| Organic matter content (%) | EN 1744-1 | <0.1 | <0.01 | <0.01 |

The Los Angeles coefficient was determined for the coarse aggregates, and the Micro-Deval abrasion or friability ratio was measured for the fine aggregates. Significantly higher abrasion values were obtained for RCA than NA, as expected *(A. Domingo-Cabo et al. 2009).* Compared to other studies, the coefficient of friability for NS was low *(Vegas et al. 2009).*

All of the aggregates presented continuous granulometry, as shown in Figure 1. In manufacturing, RCA were used to replace NA.

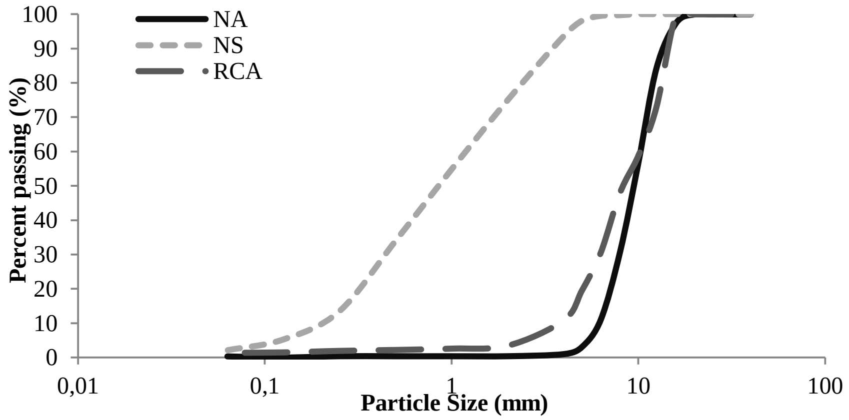


**Figure 1.** Particle size distribution

### *Water-reducing admixture*

A super-plasticiser admixture (SP) with high water reducing ability (BASF Rheobuild 1222) was used as the admixture. Because of its ability to reduce water content, this admixture improves the short-term mechanical strength, increases the durability and allows the manufacture of concrete samples with a low effective w/c.

### *Concrete mix proportions*

Eight concrete samples were manufactured in two sets to study the effect of addition of cement on concretes with two different characteristic strengths: C1 and C2, which had effective w/c ratios of 0.6 and 0.5, respectively (Table 3). Each set was divided into four groups of concrete according to their various replacement ratios of NA with RCA by weight.

**Table 3.** Nomenclature of concrete mixtures

| | C1 | | | | C2 | | | |
|---|---|---|---|---|---|---|---|---|
| | C1-0 | C1-20 | C1-50 | C1-100 | C2-0 | C2-20 | C2-50 | C2-100 |
| NA (%) | 100 | 80 | 50 | 0 | 100 | 80 | 50 | 0 |
| RCA (%) | 0 | 20 | 50 | 100 | 0 | 20 | 50 | 100 |
| w/c | 0.6 | 0.6 | 0.6 | 0.6 | 0.5 | 0.5 | 0.5 | 0.5 |

The mixture proportions are presented in Table 4. The Bolomey method was used to calculate the mixing ratios that would achieve a dry-plastic consistency.

In addition, to obtain similar mechanical strengths to control concrete, more cement was added to concrete mixtures according to ratio of RCA for all of the replacement ratios studied.

The amount of water added to achieve the desired w/c ratio was calculated based on the amount of cement added to each concrete mixture. Saturation water was added to compensate for the absorption of aggregates during the manufacturing process, as described in Tables 2 and 4. 24 four hours before each concrete mixture was produced, the humidity of the aggregates was determined and subtracted from the calculated saturation water.

**Table 4.** Concrete mix proportions

| Amount (kg/m³) | C1-0 | C1-20 | C1-50 | C1-100 | C2-0 | C2-20 | C2-50 | C2-100 |
|---|---|---|---|---|---|---|---|---|
| Cement | 300 | 309 | 320 | 336 | 375 | 386 | 399 | 420 |
| Water | 180 | 185.4 | 191.7 | 201.6 | 187.5 | 192.5 | 200 | 210 |
| NA | 1052 | 848 | 538 | 0 | 1020 | 808 | 504 | 0 |
| RCA | 0 | 211 | 538 | 1060 | 0 | 202 | 504 | 1014 |
| NS | 895 | 864 | 817.5 | 785 | 846 | 829 | 795 | 738 |
| Components total weight (kg) | 2427 | 2418 | 2405 | 2383 | 2428 | 2417 | 2402 | 2382 |
| Admixture (% of cement) | 0.33 | 0.33 | 0.33 | 0.33 | 0.53 | 0.53 | 0.53 | 0.53 |
| Saturation water | 0 | 14.7 | 37.3 | 73.6 | 0 | 14 | 35 | 70.4 |
| Workability (mm) | 39 | 38 | 36 | 32 | 37 | 37 | 37 | 34 |

In addition, the aggregates were collected to prevent variations caused by exposure to humidity. Percentages of superplasticiser equal to 0.33% and 0.53% with respect to cement were added to mixtures with w/c ratios of 0.6 and 0.5, respectively, in order to maintain the consistency of fresh concrete (35±5 mm).

*Manufacture of concrete*

One mixing method was used to produce all concrete samples. The coarse aggregates were introduced to the mixer first, followed by the addition of the fine aggregates as the mixing blades rotated. Cement was added after the first minute of homogenisation. The saturation water containing the admixture was gradually added for one minute as the mixer rotated. Finally, the blend was mixed until ten minutes to complete the concrete preparation.

The fresh concrete was introduced into moulds and shaken for two minutes. The specimens were removed from their moulds after 24 hours and cured in a curing room at a temperature of 20 °C and relative humidity of 100 %.

## *Experimental tests and results*

The following concrete properties were determined (Table 5 and 6).

**Table 5.** Mechanical and physical properties of concretes after 28 days of curing

| | C1-0 | C1-20 | C1-50 | C1-100 | C2-0 | C2-20 | C2-50 | C2-100 |
|---|---|---|---|---|---|---|---|---|
| Compressive strength (MPa) | 42.02 | 42.86 | 42.51 | 40.86 | 50.17 | 51.59 | 51.64 | 50.3 |
| Flexural strength (MPa) | 4.71 | 4.65 | 4.68 | 4.8 | 5.09 | 5.13 | 5.1 | 5.25 |
| Elastic modulus (GPa) | 27.3 | 26.2 | 25.9 | 25.1 | 30.0 | 29.9 | 27.2 | 26.4 |
| SSD Density (Kg/m$^3$) | 2.39 | 2.33 | 2.29 | 2.24 | 2.37 | 2.33 | 2.32 | 2.24 |
| Porosity (%) | 7.99 | 8.13 | 8.19 | 8.52 | 5.39 | 5.51 | 5.56 | 5.88 |
| Absorption under vacuum (%) | 9.32 | 9.96 | 10.03 | 11.21 | 7.70 | 8.31 | 8.95 | 10.82 |
| UPV (Km/s) | 4.42 | 4.36 | 4.33 | 4.22 | 4.59 | 4.44 | 4.40 | 4.32 |

### *WORKABILITY OF FRESH CONCRETE*

The consistency of fresh concrete was determined by measuring the slump in the Abrams cone (EN 12350-2), and the values are displayed in Table 4.

The amount of admixture added to maintain the slump for series C1 and series C2 was 0.33% and 0.53% of the cement weight, respectively. Workability was not affected by either the replacement percentage of RCA or the amount of cement added.

### *COMPRESIVE STRENGHT*

The compressive strengths of cubic specimens with 10 mm edge lengths were measured for both series C1 and series C2 at 1, 7 and 28 days according to UEN 12390-3. The results are shown in Figure 2.

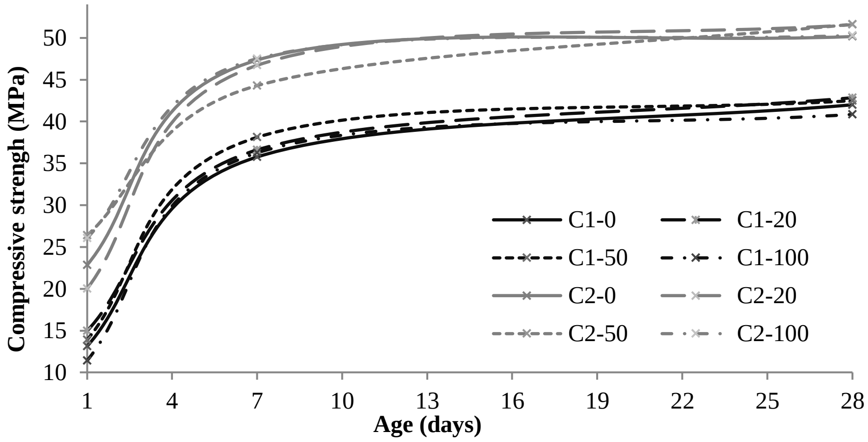


**Figure 2.** Compressive strength of series C1-C2 concrete

The compressive strengths of similarly aged specimens were comparable regardless of the replacement ratio (Figure 2). Series C1 got an average compressive strength around 42 MPa at 28 days of age. On the other hand, C2 series got an average strength equal to 51 MPa. A 12% increase in the quantity of cement produced concrete with similar compressive strength to the concrete with a 100% replacement ratio of NA by RCA. This was realised in order to compensating for the loss in strength if the same cement amount was used, as observed by *Kou et al. (2012)* and *Barbudo et al. (2013)*.

The compressive strength of series C2 was higher than that of series C1 because series C2 had a higher cement content (maximum addition equal to 12%) and lower w/c ratio (Figure 3). This is consistent with the results of *Tabsh and Abdelfatah (2009)*. They claimed that comparable compressive strength values were obtained for concrete containing RA and concrete exhibiting a high compressive strength (50 MPa).

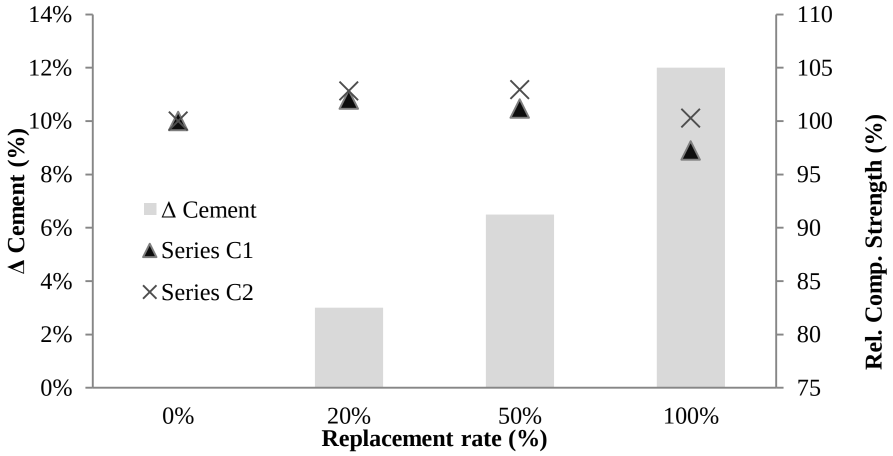


**Figure 3.** Relative compressive strength at 28 days and cement addition

*Thomas et al. (2013)* observed that using the same quantity of cement with a 20 % replacement ratio did not significantly affect the compressive strength of the concrete. Additionally, *Xiao et al. (2012)* observed that compressive strength decreased with increasing RCA content with a 20% replacement ratio. However, the present research progressively increased the amount of cement according to the replacement ratio.

***FLEXURAL STRENGTH***

Standard UNE 83316 was followed to measure the elastic modulus, and the results are listed in Table 5. As with the previous measurements, the flexural strength of series C2 was higher than series C1 because series C2 had higher cement content and a lower w/c ratio.

Similar to compressive strength, comparable flexural strengths were obtained for all replacement rates in each series. In some cases, values that were slightly higher than the control concretes were obtained (Figure 4). This result is consistent with previous studies by *Xiao et al. (2007)* and *Topçu and Sengel (2004)*, which concluded that the flexural strength of concrete containing RA did not significantly differ from control concrete.

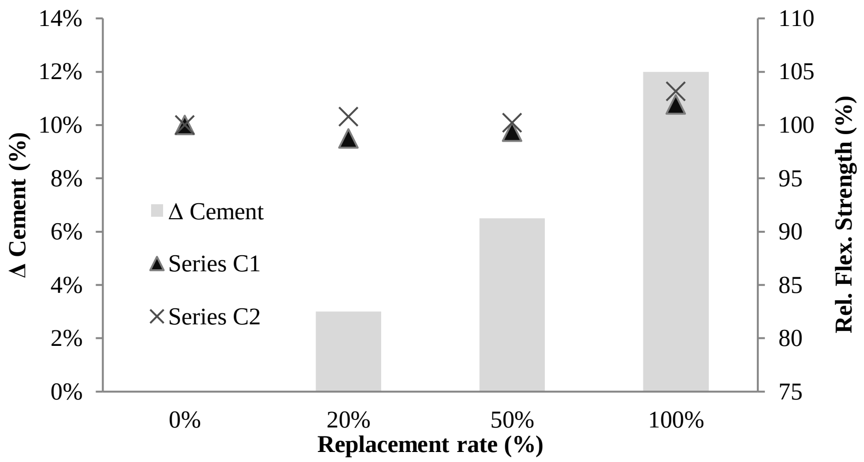


**Figure 4.** Relative flexural strength at 28 days and cement addition

***ELASTIC MODULUS***

Standard UNE 83316 was followed to measure the elastic modulus, and the results are listed in Table 5. A 4 %, 5.5 % and 8.1 % decrease in the elastic modulus was observed for series C1 concrete samples with 20 %, 50 % and 100 % replacement ratios, respectively. Similarly, a 0.4 %, 9.3 % and 12% decrease in the elastic modulus was observed for series C2 concrete samples with 20 %, 50% and 100% replacement rates, respectively.

*Katz (2003)* observed up to a 25 % decrease in the elastic modulus of concrete produced with a high replacement ratio of recycled coarse aggregates compared to control concrete. Similarly, *Kou et al. 2012* observed that concrete prepared with recycled concrete aggregates exhibited a lower elastic modulus than concrete prepared with natural aggregates.

Figure 5 demonstrates that the elastic modulus remained constant with an increasing replacement ratio of NA for both series. For this reason, the addition of cement did not improve the elastic modulus of either series that was studied. This may be because the elastic modulus of concrete is more dependent on the content of coarse aggregates than the quantity of added cement.

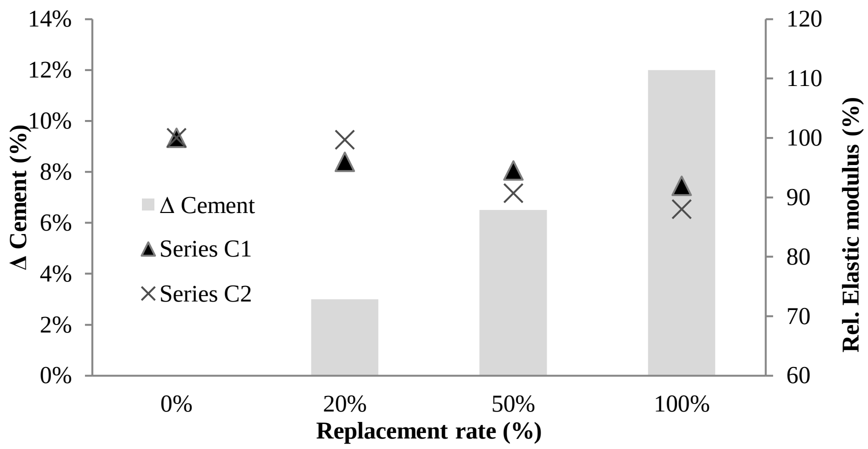


**Figure 5.** Relative elastic modulus at 28 days and cement addition

### *DENSITY AND POROSITY OF HARDNED CONCRETE*

The density of hardened concrete was measured at 28 days according to EN-12390-7, and the measurements are displayed in Table 5. The density was found to decrease with increasing NA replacement. For the 20 %, 50 % and 100 % replacement ratios, the density decreased 2.5 %, 4.2 % and 6.3 %, respectively, in series C1, and 1.8 %, 2.2 % and 5.5 %, respectively, in series C2 (Figure 6). These density measurements were compared to a control concrete in each series.

This property predominately depends on aggregate density, as affirmed by *Matias et al. (2013)*. Therefore, the addition of cement did not improve the density of the concrete.

Other studies have reported similar results. *Sanchez de Juan (2004)* observed an average decrease of 1, 2 and 3.5 % for concrete produced with 20%, 50% and 100 % recycled coarse aggregates, respectively. *Topçu et al. (2004)* demonstrated that concrete containing RA was 6% lighter (lower unit weight) and more absorptive than control concrete.

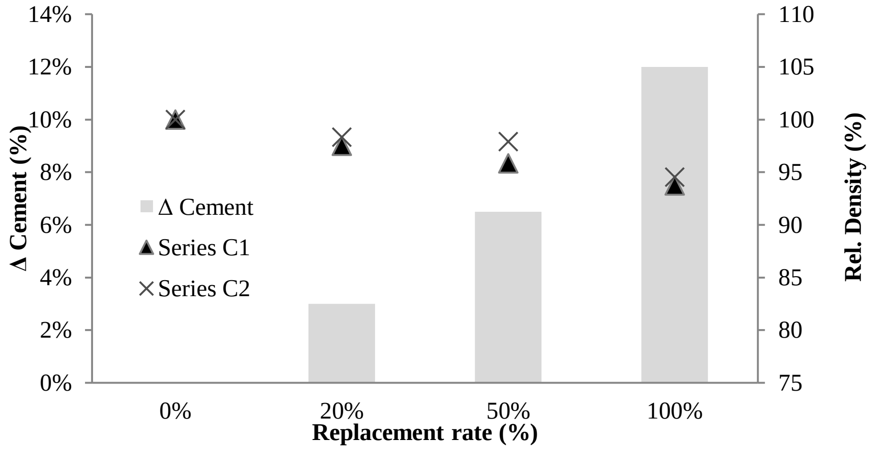


**Figure 6.** Relative density at 28 days and cement addition

In contrast, the porosity increased with increasing NA replacement in both series. For replacement ratios of 20 %, 50 % and 100 %, the porosity of series C1 and C2 increased 1.75%, 2.5 % and 6.3 %, and 2.2 %, 3.2 % and 9 %, respectively (Figure 7). Additional cement did not improve the porosity of the concrete because porosity is correlated to density.

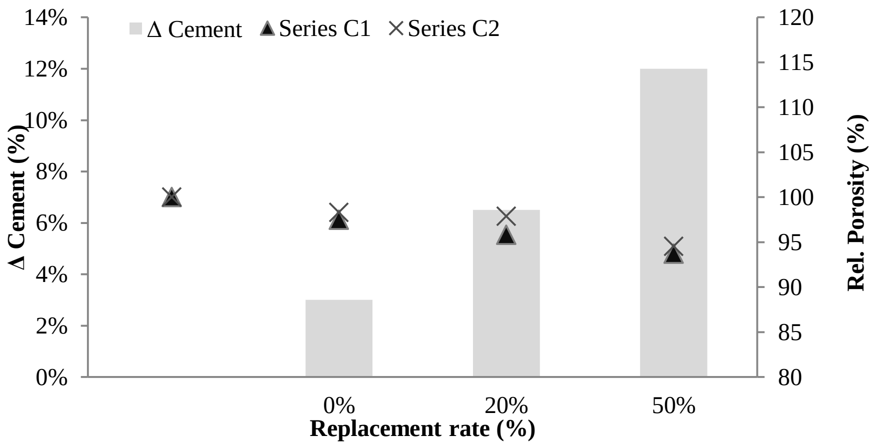


**Figure 7.** Relative porosity at 28 days and cement addition

*WATER ABSORPTION UNDER VACUUM*

Absorption properties were measured at 28 days. Each specimen was placed in a container with water, and a specific pressure was applied according to CPC 3.11. The measurements are displayed in Table 5. The absorption values for the C2 series were lower than those for the C1 series.

A distinct increase in absorption under vacuum immersion was observed as the amount of recycled aggregates increased. For replacement rates of 20%, 50% and 100%, series C1 demonstrated relative adsorption rates of 6.9%, 7.6% and 20.3%, and series C2 had relative adsorption rates of 7.9%, 16.2% and 40.5%, respectively (Figure 8).

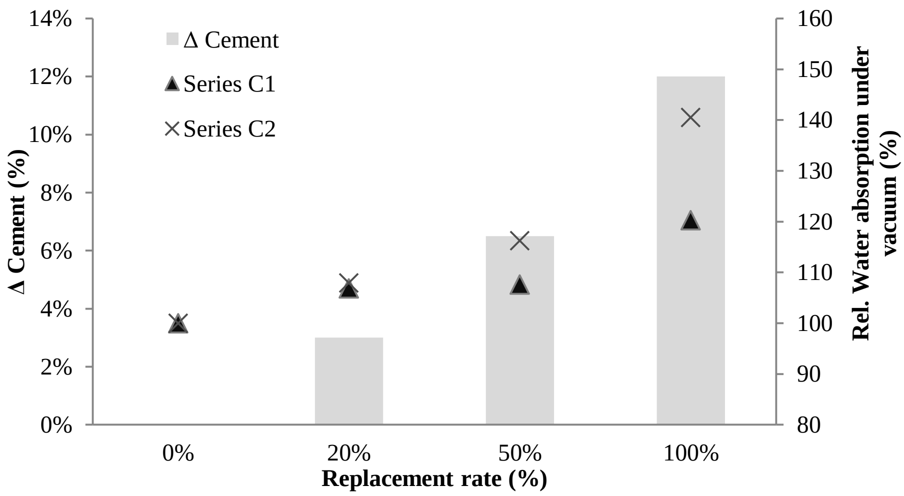


**Figure 8.** Relative water absorption under vacuum at 28 days and cement addition

As determined by the density of the hardened concrete, the water absorption under vacuum was closely related to the porosity of the sample. The water absorption under vacuum increased as the content of recycled aggregate increased. This behaviour may be because mortar adhered to the surface of the coarse aggregate concrete. The addition of cement did not affect the water absorption under vacuum. Other authors, including *Thomas et al. (2013)*, observed that the open porosity of RCA concrete samples increased compared to a control concrete with the same w/c and replacement ratios.

**UPV TEST**

The UPV test is a method that indirectly determines compressive strength (*Trtnik et al., 2009*). This test utilises two electro-acoustic transducers that act as the transmitter and receiver of ultrasonic waves with known path lengths. The velocities of the ultrasonic pulses were recorded on day 1, 4, 7 and 28 according to UNE EN 12504-4. The resulting measurements are presented in Figure 9 and show the UPV values for series C1 and series C2 concrete mixtures.

The UPV increased for concretes produced with longer curing times and a higher percentage of natural aggregates. This fact is due to ultrasonic velocity is associated with compressive strength, density, and water absorption capacity (Table 5), as determined by *Kou et al. (2011)* and *Kou et al. (2012)*.

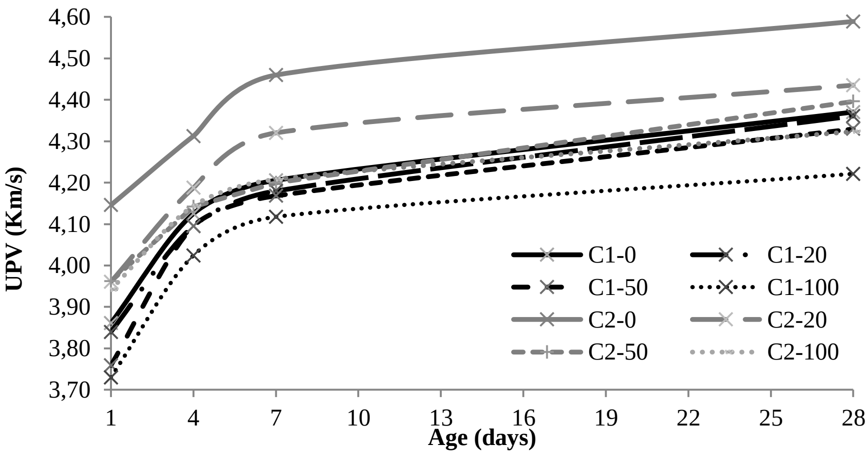


**Figure 9.** UPV of series C1-C2 concrete

The UPV test revealed similar behaviour for both the series C1 and series C2 concrete mixtures. The velocity of the ultrasonic pulses was higher for the series C2 concrete mixtures because they contained a higher cement composition, which affects the compressive and flexural strength of concrete. However, in contrast to the results of the compressive strength test, the UPV decreased with increasing replacement ratios of RCA.

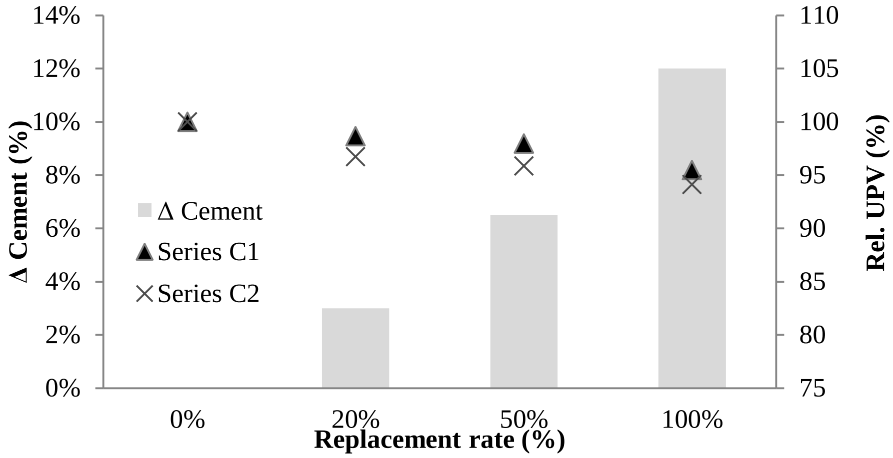


**Figure 10.** Relative UPV at 28 days and cement addition

As shown in Figure 10, the UPV decreased by 1.4%, 2% and 4.5% for series C1 concrete and 3.3%, 4.1% and 5.9% for series C2 concrete for replacement ratios of 20%, 50% and 100%, respectively.

**Table 6.** Durability properties of hardened concretes

| | Age (days) | C1-0 | C1-20 | C1-50 | C1-100 | C2-0 | C2-20 | C2-50 | C2-100 |
|---|---|---|---|---|---|---|---|---|---|
| Water penetration (mm) | 28 | 53.29 | 63.39 | 73.13 | 73.92 | 38.45 | 41.11 | 50.48 | 56.63 |
| $Cl^-$ Pen. Pool method (mm) | 56 | 17.4 | 24.76 | 26.58 | 29.25 | 9.92 | 16.17 | 19.9 | 23.45 |
| $Cl^-$ Pen. Immersion method (mm) | 56 | 21.5 | 29.06 | 30.65 | 33.14 | 10.95 | 15.85 | 21.21 | 24.69 |
| Drying shrinkage test (‰) | 180 | 0.25 | 0.34 | 0.391 | 0.413 | 0.179 | 0.223 | 0.24 | 0.330 |

### *PENETRATION OF WATER UNDER PRESSURE*

To determine the water penetration of the concrete samples, water was applied to cylindrical specimens at a pressure of five atmospheres for 28 days according to UNE-EN 12390-8. The water penetration limit was divided into two sections, as seen in Table 6.

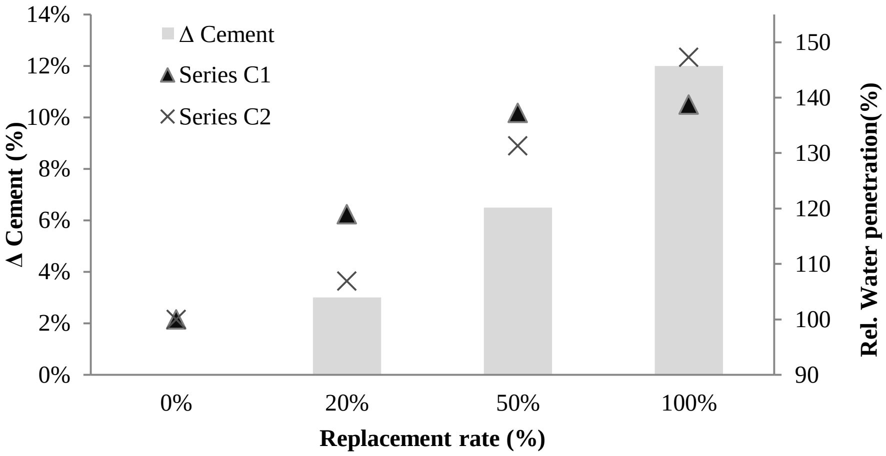


**Figure 11.** Relative water penetration at 28 days and cement addition

The penetration of water under pressure increased significantly for both series with increased NA replacement. For replacement ratios of 20 %, 50 % and 100 %, the penetration depth increased by 18.9 %, 37.2 % and 38.7 % in series C1 and 6.9 %, 31.3 % and 47.3 % in series C2, respectively, as observed in Figure 11.

*Mas et al. (2012)* [b] previously observed an increase in water penetration under pressure with a high linear proportionality by the addition of mixed recycled aggregates.

***CHLORIDE ION PENETRATION TEST***

To study the properties of concrete under aggressive environments, two different methods were applied to determine the chloride ion penetration in hardened concrete.

*"Pool" method* (A)*:* This method used 100 x 100 x 400 mm prisms that were cured for 180 days. To generate a sealed container, a polyurethane barrier was placed over the perimeter of one rectangular face of the prism. The remaining faces were waterproofed with plastic paint. Subsequently, a 20.000 ppm per litre

NaCl solution with a purity of 99.4 % *(Otsuki et al., 1992)* was added to the container. The volume of this solution was kept constant.

After 56 days of exposure, the solution was removed, and the concrete specimens were cut perpendicularly to the solution surface with a cutting machine. Subsequently, an $AgNO_3$ solution was pulverised over the cut section, and only the portions of the prism that penetrated the NaCl solution experienced a colour change. In this way, the penetration depth could be measured easily.

*Immersion method* (B)*:* This method used cylindrical specimens with a 50 mm radius and 200 mm height that had been aged for 180 days. A layer of epoxy resin was used to waterproof the lateral surfaces. Thus, only the bases were exposed to the solution when the specimens were completely immersed, as described in method A.

The specimens were extracted from the solution on day 56 of exposure and divided into two sections. Sections were impregnated with an $AgNO_3$ solution, and the penetration depth was measured.

As previously observed in the water penetration under pressure test, the penetration of chloride ions increased with increasing replacement of NA for both series regardless of the measurement method used (Figure 12). For the pool method, the chloride ion penetration was 73.1%, 85.8% and 104.5% for series C1 and 63%, 100.6% and 136.4% for series C2 (Figure 12).

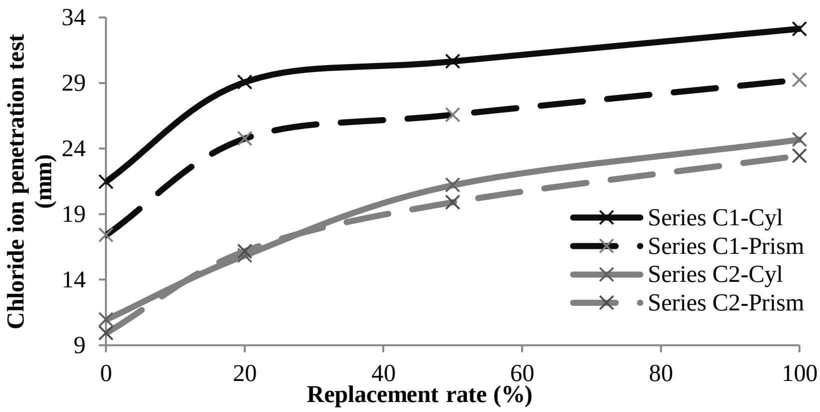


**Figure 12.** Chloride ion penetration test at 56 days of series C1-C2 concrete

In the case of immersion method, the chloride ion penetration was 95%, 105.7% and 122% for series C1 and 44.7%, 93.6% and 125% for C2 series (Figures 13 and 14). However, the depth of chloride ion penetration in series C2 concrete was less than in series C1 concrete, indicating that additional cement and the w/c ratio improved this property. This is consistent with *Meck and Sirivivatnanon (2003)*, who concluded higher chloride ion penetrations were obtained in lower quality concrete.

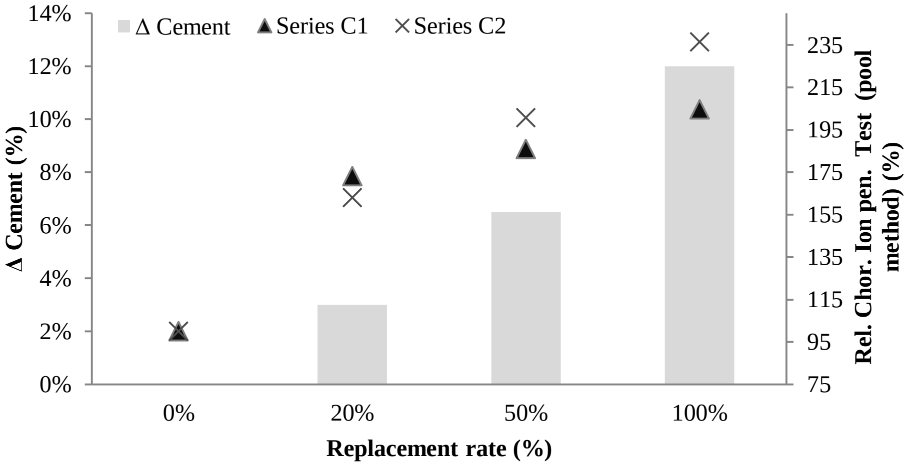


**Figure 13.** Relative chloride ion penetration test (pool method) at 28 days and cement addition

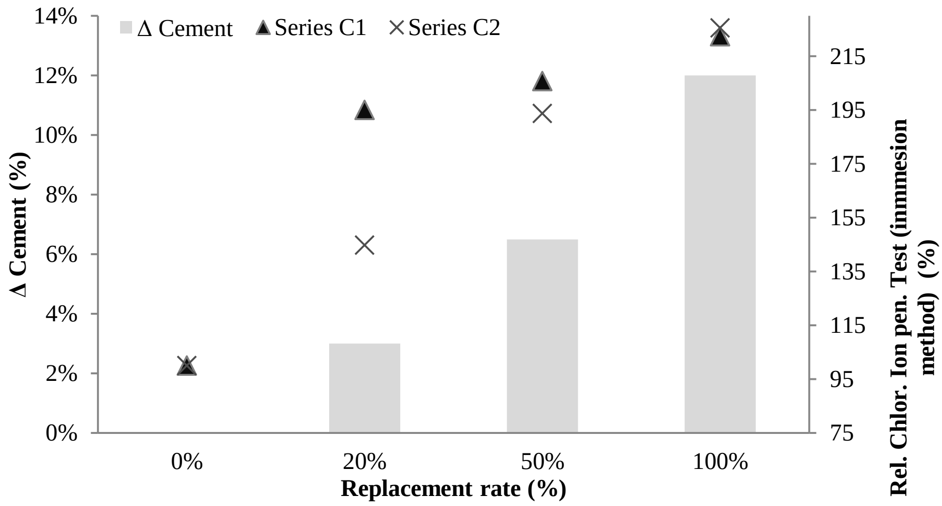


**Figure 14.** Relative chloride ion penetration test (immersion method) at 28 days and cement addition

Figure 15 depicts the correlation between the two methods used for measuring the chloride ion penetration. Correlation coefficients ($R^2$) of 0.97 and 0.99 were obtained for C1 and C2, respectively. Similar chloride penetration values were obtained by both methods (Table 6), although slightly higher values were obtained by applying the immersion method due to the specimen was completely submerged. Therefore, both methods are effective.

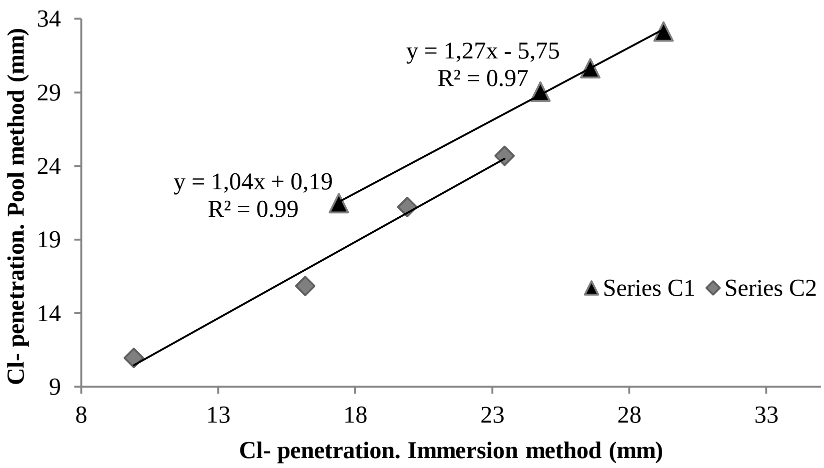


**Figure 15.** Correlation between chloride ion penetration test (pool method) and chloride penetration test (immersion method)

On the other hand, more time was required for the pool method to produce the polyurethane wall on the specimens. Additionally, the pool method was more costly and dangerous to perform because a cutting machine was used. Therefore, the results obtained by the immersion method were used for the remainder of the study.

### *SHRINKAGE*

To study the durability of the concrete samples, measurements were collected on the drying shrinkage of 100 x 100 x 500 mm concrete prisms according to ASTM C157. The specimens were exposed to an atmosphere of 50 % relative humidity at a temperature of 20 °C, and measurements were collected on day 1, 4, 7, 14, 28, 56, 90 and180, as displayed in Table 6.

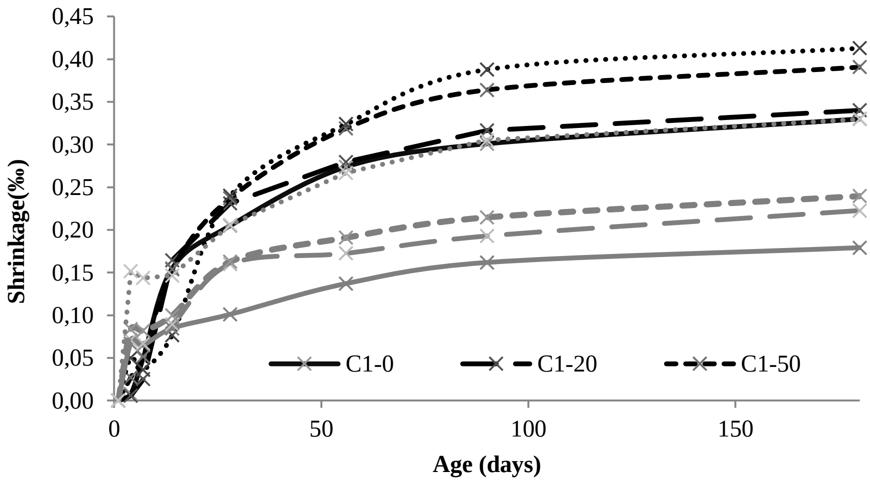


**Figure 16.** Shrinkage of series C1-C2 concrete

Figure 17 reveals that, for the two series, concrete shrinkage significantly increased with NA replacement ratio. In both cases, concrete shrinkage remained nearly constant after 180 days.

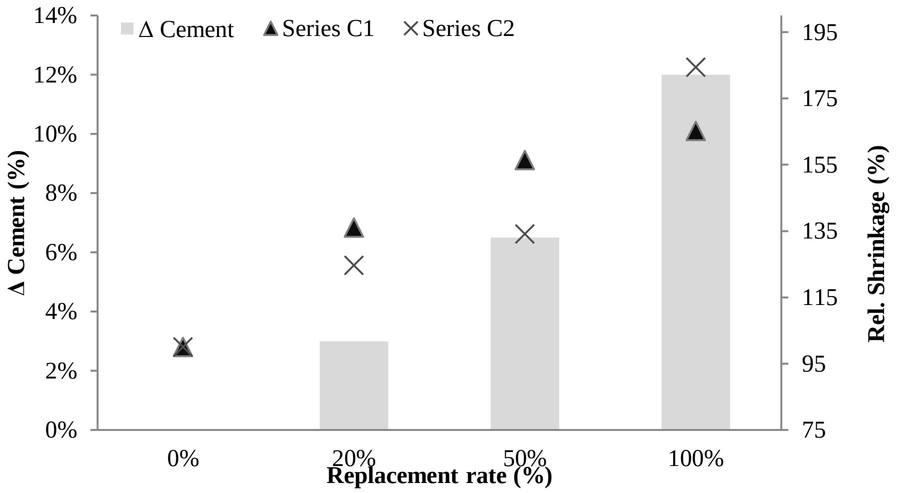


**Figure 17.** Relative shrinkage at 180 days and cement addition

In Figure 18, for replacement rates of 20%, 50% and 100%, shrinkage increased by 36%, 56.4% and 109.6% for series C1 and 24.6%, 38.1% and 84.4% for series C2, respectively.

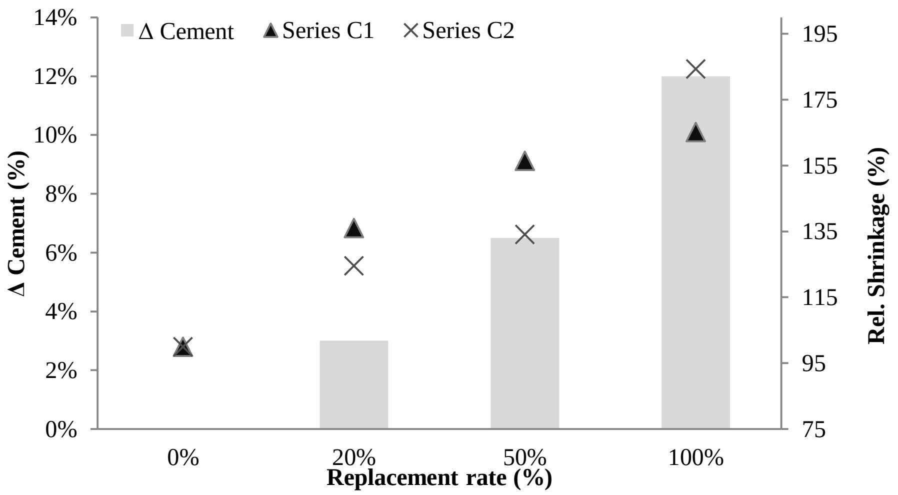


**Figure 18.** Relative shrinkage at 180 days and cement addition

In this case, the addition of cement did not reduce the dry shrinkage values of either the series C1 or C2 concrete mixtures. *Sagoe-Crentsil et al. (2001)* demonstrated that the drying shrinkage of concrete containing recycled aggregates was approximately 25 % greater than that of conventional concrete.

These results are consistent with those obtained by *Domingo Cabo et al. (2009),* who stated that shrinkage increases with an increasing amount of RCA and is significantly higher for a replacement rate of 100%.

## *Analysis inter-properties*

### *Mechanical properties*

As fixed condition of research, the compressive strength has been kept because of the increase of amount of cement for each series. Similarly, the flexural strength has been almost constant for each series due to increase of cement and the incorporation of RCA (Figure 19). Because both properties were constant for each series with the increase of cement, it is correct that the flexural and compressive strength are related.

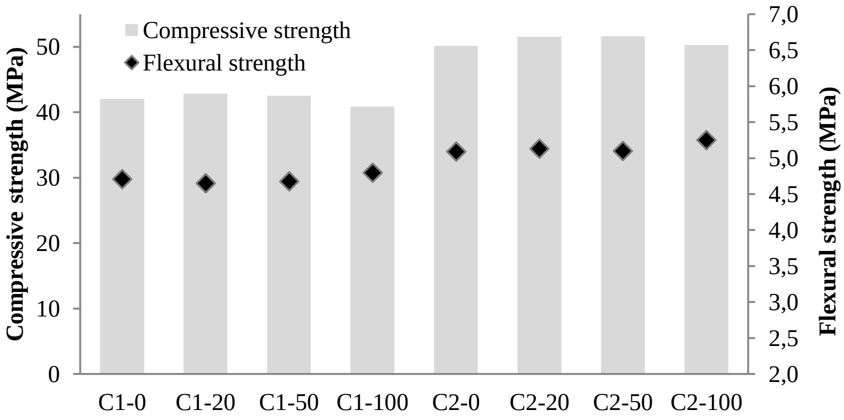


**Figure 19.** Compressive and flexural strengths at 28 days

Likewise, UPV has been constant for each series, being slightly lower with the incorporation of RCA (Figure 20).

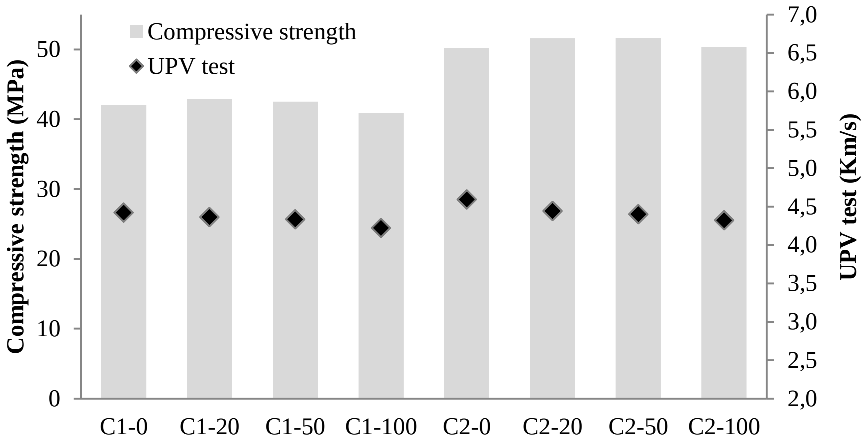


**Figure 20.** Compressive strength and UPV test at 28 days

This property is related with compressive strength and properties related to the compactness of concrete as density or porosity of the particles *(Kou et al. 2012).* For this reason, the small loss experimented on UPV could be related to the loss of density of concrete in each series, as shown in Figure 21.

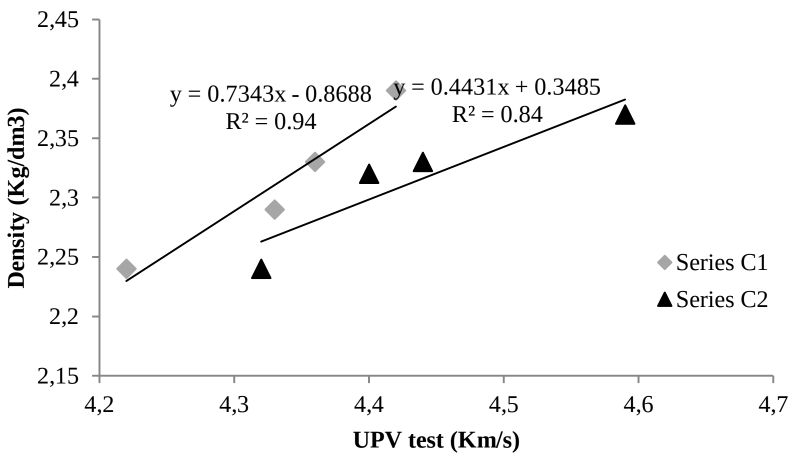


**Figure 21.** Correlation between density and UPV test at 28 days

In Figure 22 is shown the relation between elastic modulus and density, being more important in Series C2 than Series C1. The mortar adhered in the particles can be the reason of the small loss of elastic modulus, as indicated Kou et al. (2012).

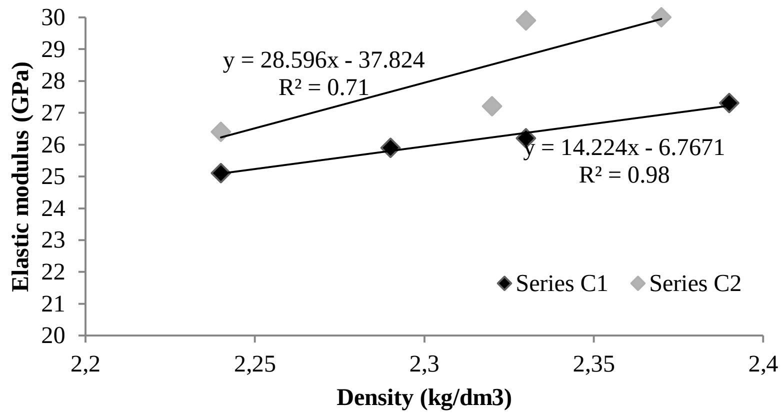


**Figure 22.** Correlation between elastic modulus and density at 28 days

***Durability properties***

Regarding the durability properties, Figure 23 shows the correlation between porosity and water absorption under vacuum. This happens due to although various different methods were used, both methods are similar with the exception that the method of water absorption under vacuum is performed without air particles in the pores.

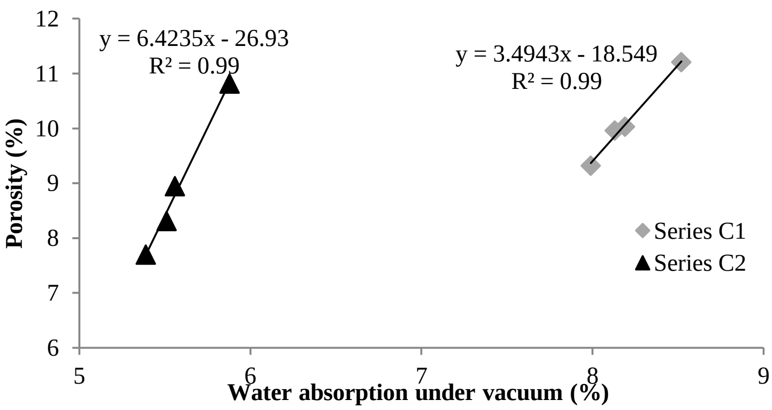


**Figure 23.** Correlation between porosity and water absorption under vacuum at 28 days

On the other hand, Figure 24 displays the correlation between the penetration of water under pressure and the chloride penetration ($R^2$ = 0.92 for series C1 and $R^2$ = 0.76 for series C2). Therefore, the depth of chloride ion penetration is a reliable indicator of the penetration of water under pressure and vice versa.

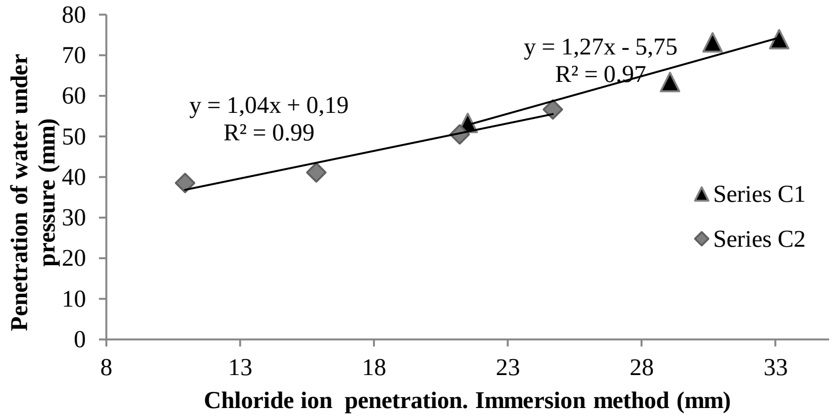


**Figure 24.** Correlation between chloride ion penetration test (immersion method) and water penetration under pressure at 28 days

Similarly, Figure 25 shows a high correlation ($R^2$ = 0.97 for C1 and $R^2$ = 0.99 for C2) between the chloride ion penetration (immersion method) and water absorption under vacuum. This phenomenon could be because of the attached mortar in the RCA, which is a determining factor in the durability of concrete.

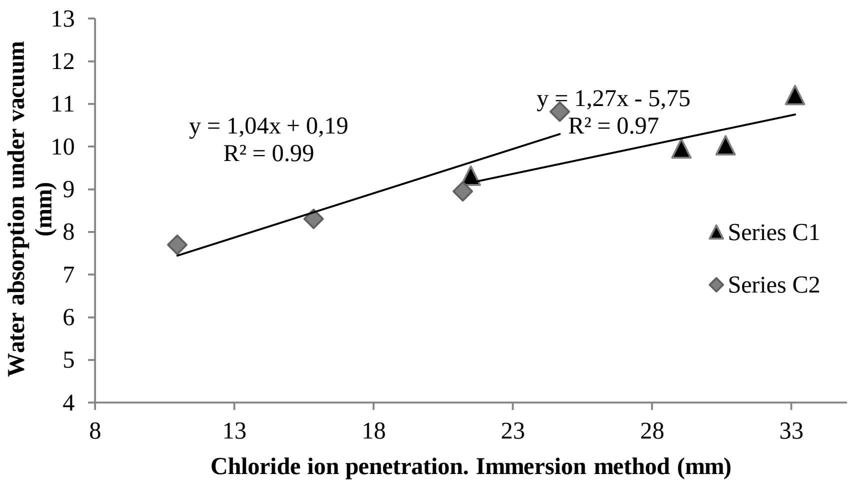


**Figure 25.** Correlation between chloride ion penetration test (immersion method) and water absorption under vacuum at 28 days

## *Conclusions*

The incorporation of recycled aggregates into manufactured concrete influences the mechanical properties and durability of the concrete. In this study, the quantity of cement used in each type of concrete was increased to compensate for the effect of the recycled aggregates and to obtain properties that are similar to those of conventional concrete. Our results led to the following conclusions:

The addition of cement to concrete mixtures utilising recycled aggregates produced concrete with comparable mechanical properties to control concretes made with the same w/c ratio. The following property changes were observed:

For both w/c ratios explored in this study, the compressive strength increased with increasing cement content in recycled aggregate concrete. To obtain the desired compressive strength of concretes containing 100 % recycled concrete aggregates, 12 % cement (by weight) should be added to the concrete mixture.

The addition of cement resulted in higher flexural strengths of the recycled concrete for both w/c ratios. Therefore, the addition of cement improved concrete strength in response to bending.

For both series, the elastic modulus decreased with increasing replacement of the natural aggregate content. Thus, the elastic modulus depends on the w/c ratio and the percentage of natural aggregates that are replaced by recycled concrete aggregates.

The UPV decreased slightly with increasing replacement ratios of natural aggregates in both series, indicating that the addition of cement does not compensate for the reduction in this property.

The durability of the concrete decreased with increasing recycled aggregate and cement content, as described in the following results:

- The water penetration under pressure, penetration of chloride ions, and drying shrinkage properties worsened as the content of recycled aggregates increased, regardless of the amount of additional cement. Therefore, the addition of cement did not improve the durability of concrete with recycled aggregates. However, for the case in which no additional cement was added, the properties would be probably considerably worse.

- Similar chloride ion penetration depths were obtained using both the "pool" method and the immersion method. However, the immersion method, which uses cylindrical specimens, is recommended because it is easier to perform and is more reliable.

- A strong correlation was observed between the penetration depth of chloride ions and the penetration depth of water under pressure. A strong correlation was also observed between the chloride ion penetration depth and the adsorption of water under vacuum.

In summary, the addition of cement to recycled concretes is recommended to compensate for the loss in mechanical properties that is typically observed when the content of natural aggregates is replaced. Although the addition of cement did not significantly improve concrete durability, it helped to offset the loss of durability for concretes made with recycled aggregates.

## Acknowledgements

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## UBLICACIÓN 3. MECHANICAL AND DURABILITY PROPERTIES OF CONCRETES MANUFACTURED WITH BIOMASS BOTTOM ASH AND RECYCLED COARSE AGGREGATES.

La tercera aportación también fue publicada en una revista indexada en JCR. Esta publicación surge como resultado de la Fase 3 expuesta en la metodología de esta Tesis Doctoral.

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Mechanical and durability properties of concretes manufactured with biomass bottom ash and recycled coarse aggregates

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## *Abstract*

Recycled materials of various types have been used as substitutes for coarse recycled aggregates and natural sand in the manufacture of concrete. Generally, the values of mechanical and durability properties decreases when applying different replacements of natural aggregates with recycled aggregates in both fine and coarse granulometries.

However, new waste from the combustion of biomass as bottom ash has not been applied as a substitute for fine aggregate in the manufacture of concrete. In this research, concrete consisting of recycled aggregate substitutions was manufactured by applying different replacement rates of natural sand with biomass bottom ash. An efficient dosage method can be applied to obtain an optimal ratio of recycled concretes made with biomass additions.

Mechanical properties and durability were evaluated in order to know the possibilities of applications in real concretes with these wastes. The results showed a reduction in the properties of mechanical properties around 22%, but the decreasing in durability was higher than it can be waited.

## *Keywords*

Biomass, bottom ash, concrete, durability, recycled aggregates.

## *Introduction*

In civil constructions, the use of recycled aggregates (RA) in the manufacture of concrete is growing. This increase is a result of the environmental benefits, rather than the advantages in mechanical and durability behaviours presented by recycled waste. Thus, it is partially accepted that there are losses in the mechanical and durability properties for these recycled concretes.

Traditionally, the use of recycled aggregates for their application in construction elements, such as sub-bases for roads or embankments, was focused on a particular type, the recycled concrete aggregate (RCA). Agrela et al. [1] used RA treated with cement in the road sub-base for an access to a highway located in Malaga, Spain.

In recent decades, several studies have been performed on the concrete application substitutions of natural aggregates using RCA to verify their mechanical properties and durability. Kwan et al. [2] studied the mechanical and durability properties in concrete with RCA, and Kou et al.[3] studied the behaviour of concrete with natural aggregate and RCA using mineral admixtures.

Alternatively, International union of laboratories and experts in construction materials, systems and structures (RILEM) in its report containing recommendations for coarse recycled aggregates, included recycled mixed aggregates (RMA) in a mix of crushed masonry and concretes for the manufacture of new concretes [4].

However, the use of recycled mixed aggregates from crushed bricks and masonry is increasingly being investigated for their use in concrete and other construction elements. Mas et al. [5] studied the behaviour of non-structural concretes made with different amounts of RMA, and Martinez-Lage et al. [6] studied the physical-mechanical properties in plain concretes made with RMA.

Generally, many authors concluded that the replacement of NA by RA resulted in lower compressive strength values [7-8], lower flexural strength [9] and a modulus of elasticity [10] than the reference concrete. As for the durability properties, many authors have concluded that high RA rates cause significant degradation in certain properties such as penetration of water under pressure and chloride ion penetration, and it is obtained higher shrinkage values [5,11].

Regarding the use of RA as a fine fraction, various investigations have been conducted using these types of concrete aggregates to study their properties [12-13]. Similarly, several studies have incorporated the mineral additions of fly ash, blast furnace slags and metakaolin as an ordinary Portland cement substitution [3, 14].

More residues from industrial processes could be applied in the manufacture of concrete for the environmental benefits it affords, if the final concrete did not result in an important reduction in mechanical property values as occurs in recycled concretes with RA.

In Andalusia, a region located in southern Spain, there are a large number of biomass power plants, which primarily use olive residues. These plants produce electrical power and two types of residues are obtained: biomass fly ash (BFA), formed by particles that are washed away by the gas stream to the outside of the combustion chamber and used for agricultural fertiliser, and biomass bottom ash (BBA), formed by particles not combusted [15] which is transported to landfills or dumps because the properties of these residues related to the mechanical behaviour in civil applications are not well known. Some studies have characterized physically and chemically the BBA. BBA has low density, high porosity and a high percentage of organic matter content [16-18]. Regarding BBA pozzolanic capacity, other studies have concluded that the presence of CaO in the combustion of biomass, such as olive wood, might limit the use of this type of fly ash because of its low pozzolanicity [18].

Furthermore, BFA has been studied for its possible use in the manufacture of concretes and mortars, replacing cement content. Cuenca et al. [15] concluded that the compressive strength in concretes prepared with substitutions by Ordinary Portland Cement (OPC) by BFA was slightly higher than those in self-compacting concrete. Maschio et al. [19] concluded that similar values of compressive strength and absorption were obtained for mortars that contained 5% BFA and that the properties declined with replacements that contained 10%, 20% and 30%, because of the high porosity.

However, the use of biomass bottom ash (BBA) has not been sufficiently studied. This ash presents different properties than BFA, characterised by a larger grain size and higher humidity, making it suitable for applying in road sub-grades, non-structural concretes, or embankments [16, 18].

In this study, the BBA from the combustion of olive tree prunings was studied for its applicability in several substitutions of cement and natural sand in non-structural recycled concretes. The characterisation properties of BBA and RA were determined and then applied in the manufacture of recycled concrete. Additionally, physical (density, porosity and water absorption), mechanical (compressive and flexural strength) and durability properties (chloride and water penetration under pressure, shrinkage) of recycled concretes with different replacement percentages of cement and natural aggregates were studied. This paper presents findings concerning dosages, optimal replacements or modifications of properties in the application of RA and BFA in the manufacture of concrete.

## Materials and methods

### Materials

### Cement

The cement used in the study was ordinary Portland cement (OPC), CEM I according to ASTM C150. It has a pure grey clinker, a characteristic strength of 42.5 MPa, and hardens rapidly. This cement is considered sulphate resistant because it has a low content of aluminium. All the chemical properties are summarised in Table 1.

**Table 1.** Properties of cement

| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $K_2O$ | $Na_2O$ | Granul. 45µm | Granul. 32µm | Blaine E. S. | Loss of ignition |
|---|---|---|---|---|---|---|---|---|---|---|---|
| % | % | % | % | % | % | % | % | % | % | cm2/g | % |
| 20.18 | 4.14 | 4.51 | 63.75 | 0.91 | 3.24 | 0.75 | 0.31 | 6.2 | 16.1 | 3701 | 1.44 |

### Biomass Bottom Ash

As a fine fraction substitute, the bottom ash from the combustion of several biomass compounds (BBA) was used, coming from the thermal plant located in the village of Linares, Jaen, (Spain). BBA is a residue generated from the combustion of biomass composed primarily of olive mash and other biomass, such as olive orchard prunings as well as other energy crops.

The process begins with the introduction of these products into the biomass-fuelled steam. Inside, the biomass is burned by a boiler at a temperature of 403 ºC to naturally circulate heated water for steam. The BBA is obtained from a wet extraction system.

The maximum particle size is 6 mm, but the fraction between 2 mm and 6 mm was removed to reduce the content of non-combusted particles. Figure 1 shows the BBA samples with the original granulometry and the processed 0–2 mm BBA. The properties of BBA are summarised in Table 2.

**Table 2.** Properties of recycled and natural aggregates

| | | CG | MG | RCA | RMA | BBA | NS | EHE-08 |
|---|---|---|---|---|---|---|---|---|
| Size (mm) | EN 933-1 | 16-31.5 | 4-16 | 4-31.5 | 4-31.5 | 0-2 | 0-4 | - |
| SSD Density (mg/m$^3$) | EN-1097-6 | 2.63 | 2.68 | 2.22 | 2.36 | 2.02 | 2.59 | - |
| Absorption (%) | | 0.80 | 1.53 | 6.94 | 7.02 | 19.9 | 1.09 | 5% |
| Los Angeles (%) | EN-1097-2 | - | 20 | 29 | 33 | - | - | 40 |
| Friability ratio (%) | EN-83-115 | - | - | - | - | 29 | 12 | 40 |
| Sulphur content (%) | EN-1744-1 EN-1744-1 | <0.01 | <0.01 | 0.30 | 0.98 | 0.21 | <0.01 | 1% |
| Soluble sulphate (%$SO_3$) | EN-1744-1 | <0.01 | <0.01 | 0.85 | 1.01 | 0.47 | <0.01 | 0.8 |
| Chlorides (%) | EN-1744-1 | 0.08 | 0.1 | 0.025 | 0.04 | 0.21 | <0.01 | 0.05 |
| Organic matter content (%) | EN 1744-1 | <0.1 | <0.1 | <0.01 | 0.4 | 3.06 | <0.01 | 1% |

***Recycled Aggregates***

Two types of recycled aggregates were used in this research whose particle-size distribution is shown in Figure 1 and physical and chemical properties are in Table 2:

- Recycled aggregate from the crushing of concrete blocks and mortar (RCA), from plants in El Cabril (Córdoba), whose composition is shown in Table 3;

- Mixed recycled aggregate (RMA) from the crushing of concrete blocks and masonry blocks from the treatment of CDW in Gecorsa (Córdoba), whose composition is shown in Table 3.

**Table 3.** Composition of recycled aggregates from CDW

| | RCA | RMA |
|---|---|---|
| Bituminous particles | 1% | 7% |
| Ceramic particles | - | 14% |
| Concrete / mortar | 83% | 55% |
| Natural Aggregates | 16% | 22% |
| Plaster (gypsum) | - | 1% |
| Others | - | 1% |

**Natural Aggregates**

Three types of natural aggregates were used in the manufacture of concrete: natural coarse gravel (CG), natural medium gravel (MG) and natural sand (NS) with a granitic nature from "La Serena" (Badajoz). The properties of the aggregates are shown in Table 2 and their particle-size distribution is shown in Figure 1.

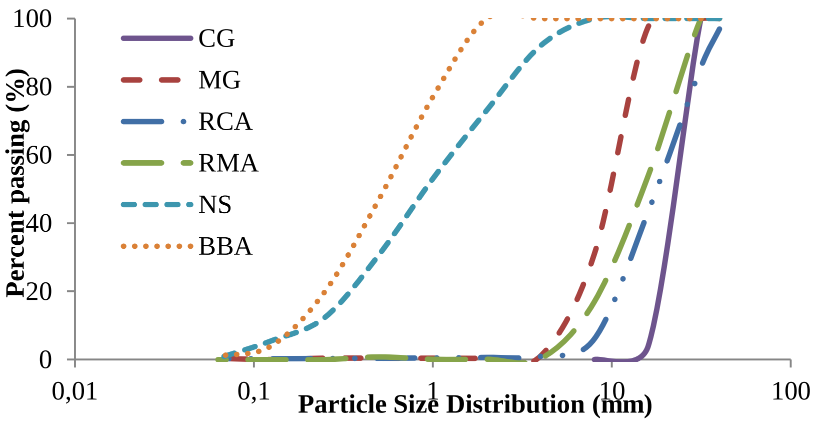


**Figure 1.** Particle size distribution

***Comparison of aggregate properties***

All of the aggregates present continuous granulometry. As it can be deduced from the sizes shown for each material, the RCA and RMA will replace the mix of CG and MG called natural gravel (NG) in the manufacture of concrete and BBA will replace NS.

With regards to the values of saturated surface dry density (SSD density) and absorption, the SSD density is higher in natural aggregates than in recycled aggregates, and absorption is higher in recycled aggregates. This is to be expected because of the presence of adhered mortar in the RCA [20] and the high absorption and low density of ceramic aggregate [21].

The lowest SSD Density value corresponds to the BBA, approximately 2 kg/dm$^{3.}$ This value was lower than that obtained by Evangelista et al. [13] for a recycled fine aggregate (2.16 kg/dm$^3$) or Kou and Poon [22], who determined a SSD Density of 2.19 kg/dm$^3$ for a furnace bottom ash.

With regards to the water absorption at 24 hours, the BBA presented the highest value, approximately 20%. A higher absorption (28.9%) was obtained by Kou and Poon (2009) [22] for a furnace bottom ash. The absorptions of the natural aggregates ware low. However, RCA and RMA had high absorption (6.94% for RCA and 7.02% for RMA), these values being outside the Concrete Spanish Instruction (EHE-08) [21].

As for the abrasion test, the coefficient of Los Angeles was determined for the coarse aggregate and micro-Deval abrasion, or friability ratio, for the case of fine aggregates. The highest value corresponded to the recycled aggregates that were slightly higher for the RMA (Table 2) Due to the content of ceramic particles and the adhered mortar [20]. Furthermore, the friability ratio of the BBA was higher than that of the NS. This value is very high compared to the work performed by Vegas et al. [23], who obtained an average of 26 for 6 fine recycled aggregates analysed.

Regarding the chemical properties, all aggregates are within the requirements of the (EHE-08) [24], except the BBA, which contained values for chlorides and organic matter content that were higher than permitted, and the soluble sulphates or RMA.

***Water-reducing admixture***

A super-plasticiser additive (SP), type BASF Rheobuild 1222, was used. The objective was to reduce the mixing water, improving the mechanical strength in the short term by increasing the durability and allowing the concrete to be manufactured with a low effective water/cement ratio (w/c) because of its high water reduction.

***Concrete mix proportions***

Nine batches of concrete were manufactured and divided into 3 groups according to the type of coarse aggregate used and the amount of BBA, as shown in Table 4.

The effective w/c ratio was 0.6 for all cases. Similarly, the amount of cement (300 kg/m$^3$) and slump (8–9 cm) were the same for all manufactured concretes. The Bolomey method was used to calculate the mixture proportions shown in Table 4.

The total water shown in this table corresponds to the mix water calculated in 300 kg/m$^3$ of cement plus the saturation water of the recycled aggregates (RA) and BBA. These amounts decreased depending on the moisture present in each of the aggregates.

**Table 4.** Concrete mix proportions (Kg/m$^3$)

| | BBA-0/ NG | BBA-3/ NG | BBA-6/ NG | BBA-0/ RCA | BBA-3/ RCA | BBA-6/ RCA | BBA-0/ RMA | BBA-3/ RMA | BBA-6/ RMA |
|---|---|---|---|---|---|---|---|---|---|
| Cement | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 |
| Total water | 180 | 183 | 186 | 228 | 231 | 234 | 226 | 229 | 232 |
| CG | 447 | 447 | 447 | 0 | 0 | 0 | 0 | 0 | 0 |
| MG | 662 | 662 | 662 | 0 | 0 | 0 | 0 | 0 | 0 |
| RCA | 0 | 0 | 0 | 985 | 985 | 985 | 0 | 0 | 0 |
| RMA | 0 | 0 | 0 | 0 | 0 | 0 | 942 | 942 | 942 |
| NS | 829 | 794 | 770 | 868 | 842 | 816 | 846 | 820.5 | 795 |
| BBA | 0 | 24.6 | 49.2 | 0 | 26 | 52 | 0 | 26 | 52 |
| Superplasticizer | 3 | 3.9 | 4.5 | 3 | 3.9 | 4.5 | 3 | 3.9 | 4.5 |

## *Manufacture of concrete*

The same mixing method was used for all concretes. First, the coarse aggregate was introduced to the mixer, followed by the fine aggregate and 50% of the total water. The mixture was homogenised for five minutes of mixing. Later, the cement and the additive dissolved in the remaining water were added and mixed for 10 minutes.

Then, the slump was determined (8–9 cm) and the specimens were manufactured. After 24 hours, the specimens were removed from their moulds and cured in the curing room at an ambient temperature of 20 °C and 100% relative humidity.

## *Experimental tests and results*

Following are the experimental tests on the hardened concrete.

**Table 5.** Physical and mechanical properties of fresh and hardened concrete

| | Age | BBA-0/ NG | BBA-3/ NG | BBA-6/ NG | BBA-0/ RCA | BBA-3/ RCA | BBA-6/ RCA | BBA-0/ RMA | BBA-3/ RMA | BBA-6/ RMA |
|---|---|---|---|---|---|---|---|---|---|---|
| Workability | | 9 | 8 | 8 | 9 | 8 | 7.5 | 8 | 8.5 | 8 |
| Compressive Strength (MPa) | 7 | 29.8 | 29.6 | 27.5 | 26.5 | 24.5 | 22.8 | 22.9 | 22.2 | 21.7 |
| | 28 | 44.3 | 37.7 | 35.4 | 35.9 | 33.3 | 30.1 | 32 | 30.4 | 27.7 |
| | 90 | 48.5 | 42.2 | 39.8 | 40.8 | 39.7 | 34.2 | 37.3 | 34.9 | 30.5 |
| Flexural Strength (MPa) | 28 | 5.9 | 4.9 | 4.7 | 4.9 | 4.6 | 4.5 | 4.4 | 4.3 | 4.1 |
| Density (Kg/m$^3$) | 28 | 2363 | 2336 | 2328 | 2178 | 2177 | 2174 | 2149 | 2144 | 2141 |
| Absorption (%) | 28 | 5.7 | 5.9 | 6.3 | 6.5 | 6.9 | 7.6 | 6.7 | 7.2 | 7.7 |

### *Workability*

The consistency of fresh concrete was measured by the slump in the Abrams cone (EN 12350-2), providing the values displayed in Table 5.

To maintain the same slumps with the incorporation of the BBA, different amounts of super-plasticiser were applied: 0.01%, 0.013% and 0.015% of the cement weight for the replacement of 0%, 3% and 6% of the NS by the BBA, respectively (Table 4).

Thus, the replacement percentage of the RCA or RMA did not alter the workability in any way.

### *Compressive strength*

The compressive and flexural strengths were applied using a hydraulic press with a maximum capacity of 2000 KN, which was applied at a constant speed load. The compressive strength was applied using the standard EN 12390-3 on cubic specimens with 100-mm sides, for 7, 28 and 90 days.

Table 5 shows the results for the compressive strength of the concrete made. An increase is observed according to the curing age (Figures 2-3), as expected by *Katz* [10] and Kou et al. [25]. Similarly, approximately 75% of the compressive strength at 28 days was obtained at only 7 days for the entire series, as obtained by Kou et al. [12] and Limbachiya et al. [26].

The incorporation of the recycled aggregates (RCA and RMA, and 0% BBA) caused an average decrease of approximately 15% and 25% (or 19% and 28% at 28 days) of the compressive strength of the concrete reference (BBA-0/NG), respectively, for the 3 ages series and for 100% of the replacement (Figure 2). This is consistent with the 23% loss of compressive strength for a 100% NG substitution of RMA by Martinez-Lage et al. [6] for 150 x 300 mm cylindrical specimens at 28 days. Similar results were obtained by Kou et al. [25] in concretes with RCA, where a loss of 24.5% average strength was obtained for three different series of concretes with different substitutions of natural aggregates by RCA.

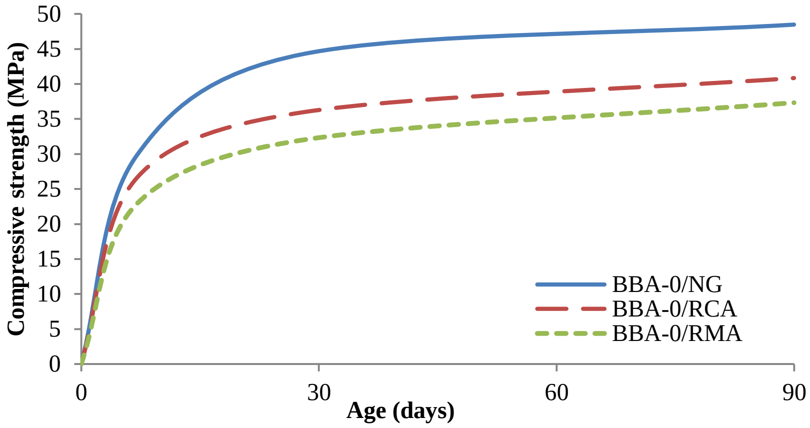


**Figure 2.** Evolution of compressive strength. Concretes without BBA

Alternatively, compressive strength decreased according to an increase in the BBA amount for all ages and all series (Table 5 and Figure 4). Thus, 3% and 6% incorporation of BBA, without recycled aggregates, caused a decrease equal to 15% and 20% compressive strength of the reference concrete (BBA-0/NG). Therefore, the loss of compressive strength is not proportional to the amount of BBA incorporated.

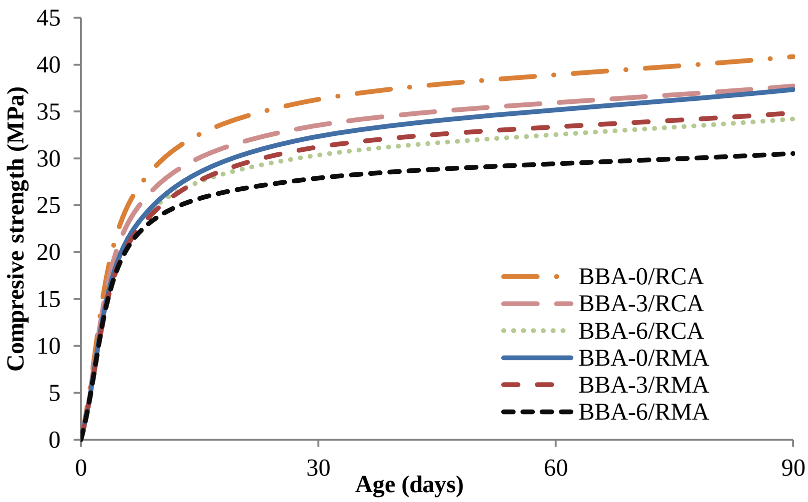


**Figure 3.** Evolution of compressive strength. Concrete with RCA/RMA

Regarding the effect of the joint incorporation of BBA and RA, the decrease of the compressive strength was approximately equal to RCA with RMA for the different BBA incorporation ratios (Table 5). Consequently, the recycled aggregates (RMA or RCA) did not influence the BBA's effect on the compressive strength.

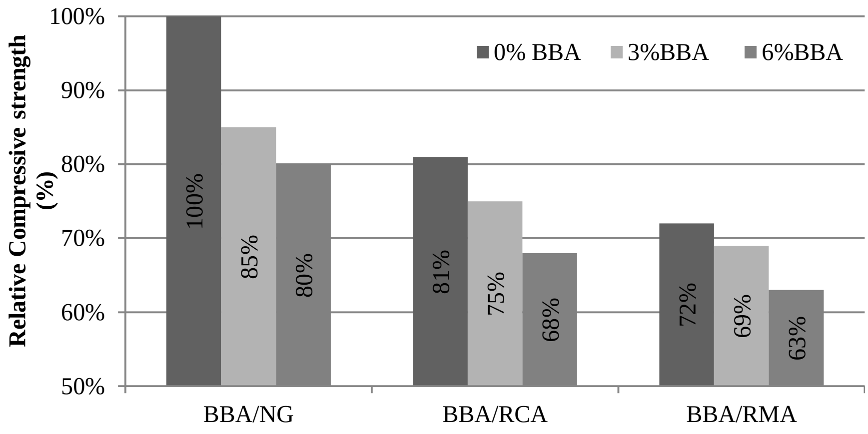


**Figure 4.** Comparison of compressive strength at 28 days with respect to reference concrete *(BBA-0/NG)*

Regarding the effect of the joint incorporation of BBA and RA, the compressive strength decreased with the incorporation of BBA, being slightly higher for concretes with RMA (25–32% for replacement rates of 3% and 6%, respectively, in the RCA series, and 31–37% for replacement rates of 3% and 6%, respectively, in the RMA series).

***Flexural strength***

The flexural strength was determined using prismatic specimens with the dimensions 100 x 100 x 150 $mm^3$ cured for 28 days. This property was determined according to EN 12390-5.

Regarding the flexural strength, the values obtained are shown in Table 5. As occurred with the compressive strength, the flexural strength declined with the incorporation of RA: 18% and 27% at 28 days for the RCA and RMA series (Figure 5), respectively. Other studies also obtained significant decreases. Katz

[10] obtained a loss of flexural strength at 28 days of 32% to 100% concrete with RCA and Portland white cement. Similar to concrete with ordinary Portland cement, the loss of strength was 12%.

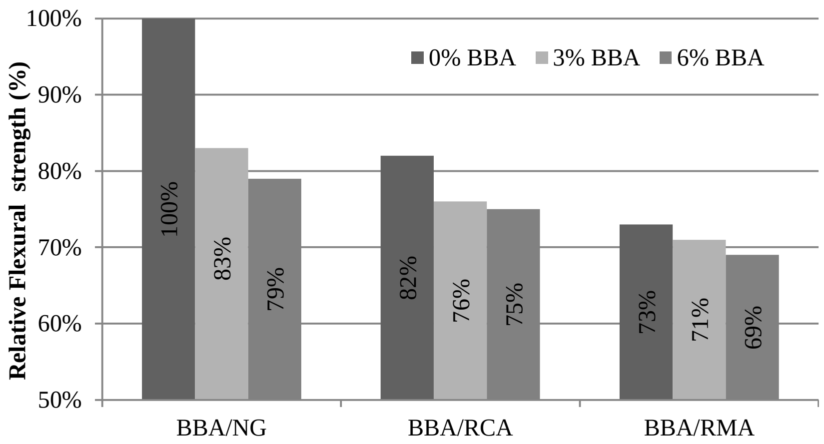


**Figure 5.** Comparison of flexural strength at 28 days with respect to reference concrete (BBA-0/NG)

Alternatively, the addition of BBA to concrete with NG (the BBA/NG series) affected the flexural strength adversely. In these, the flexural strength reductions were 17% and 21% for the additions of 3% and 6% BBA, respectively.

Additionally, as occurred in the compressive strength results, the flexural strength loss was significantly higher in the RCA and RMA series than in NG.

Figure 6 shows the excellent correlation between the compressive strength and flexural strength for all concretes ($R^2$=0.94). Compressive strength can reliably determine the flexural strength for each concrete and vice versa.

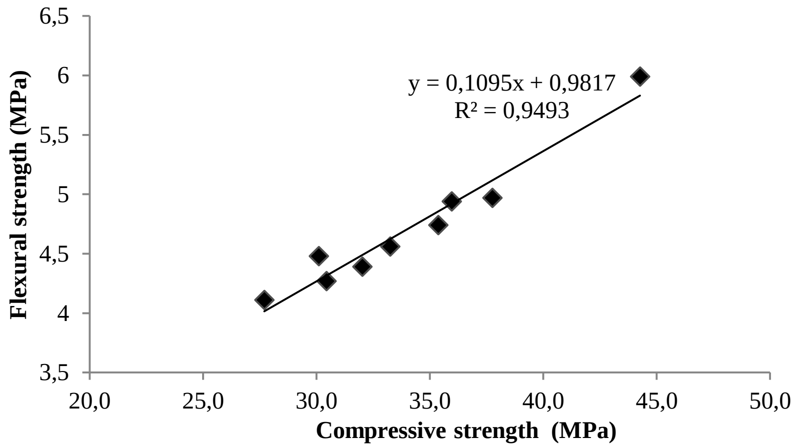


**Figure 6.** Correlation between compressive strength and flexural strength at 28 days

***Density and absorption of hardened concrete***

These properties were determined at 28 days according to EN-12390-7 in the reception conditions after 28 days of curing in a moist chamber. To determine the volume, real measures were performed on each specimen at 100% humidity and 20°C after 15 minutes.

The results of density of the hardened concrete are given in Table 5. The apparent density of the concrete decreased as the natural aggregate replacement increased with RA and/or BBA. This property is mainly dependant on the density of the aggregates used, as affirmed by Matias et al. [27].

As expected, the reference concrete (BBA-0/NG) obtained the highest density values, and these values decreased approximately 9% with the incorporation of RA. This result agrees with other studies. Martínez-Lage et al. [6] obtained a concrete density loss of approximately 8% to 100% replacements.

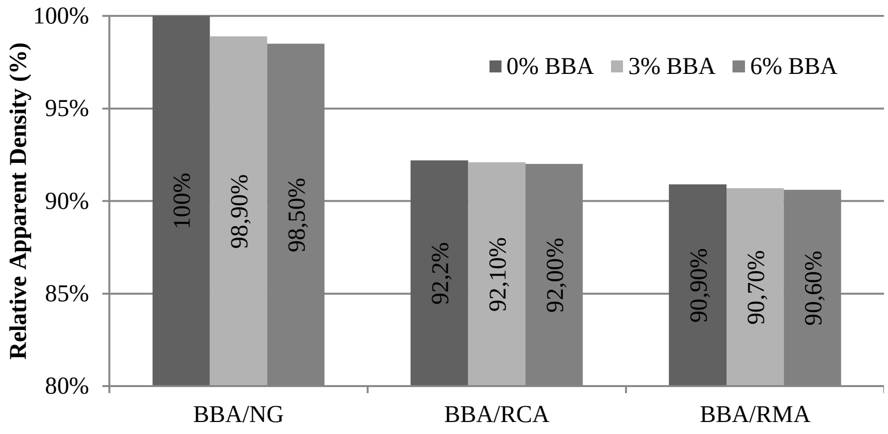


**Figure 7.** Comparison of density at 28 days with respect to reference concrete (BBA-0/NG)

Regarding the influence of BBA, the reductions were not significant with this value. Figure 7 shows that the apparent density reductions do not exceed 2.5%.

Similar results occurred for the BBA/RCA and BBA/RMA series, in which no losses occurred at a saturated density below 1% with respect to the same concretes without BBA.

The replacement of NG by RA (RCA and RMA) has caused a significant increase in the absorption. As shown in Figure 8, there was an increase of 15% and 18% for BBA-0/RCA and BBA-0/RMA, respectively.

The absorption was negatively affected by the BBA. Figure 8 shows an increase in the absorption associated with the incorporation of the BBA (5% for a 3% replacement of BBA and 11% for a 6% replacement of BBA) in relation to the BBA-0/NG control. Furthermore, similar absorption increases were obtained for the BBA/RCA series and the BBA/RMA series with the increasing BBA. Figure 8 shows the average increase of 7% and 15% to 3% and 6%, respectively. The incorporation of BBA did not significantly alter the concrete's SSD density with respect to the reference concrete, and the absorption increased proportionally to the addition of BBA.

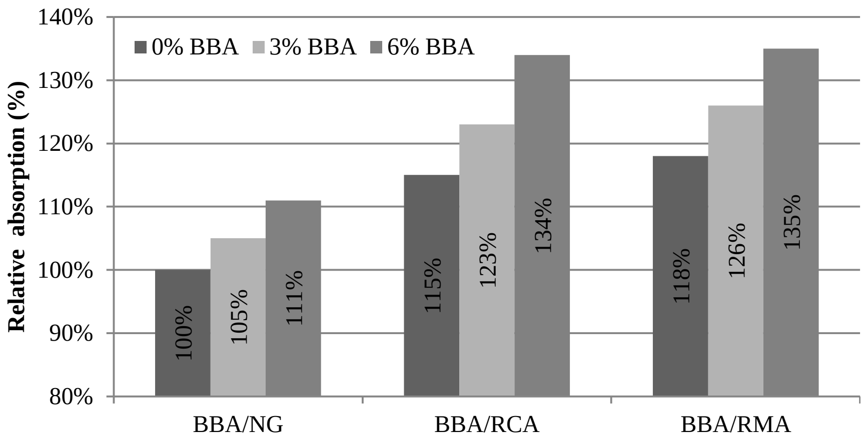


**Figure 8.** Comparison of absorption at 28 days with respect to reference concrete (BBA-0/NG)

### *Penetration of water under pressure*

To determine the penetration of water in concrete, water was applied to the cylindrical specimens at 5 atmospheres of pressure according to UNE-EN 12390-8 at 28 days.

Table 6 shows the results of the penetration of water under pressure. The penetration of water significantly increased with the incorporation of RA, increasing by 81% for BBA-0/RCA and 95% for BBA-0/RMA with respect to the control concrete (Figure 9). Furthermore, the penetration of water was adversely affected by the addition of BBA, increasing by 69% and 110%, respectively, for the replacements of 3% and 6% of NS by BBA.

**Table 6.** Durability properties of hardened concrete

| | Age | BBA-0/NG | BBA-3/NG | BBA-6/NG | BBA-0/RCA | BBA-3/RCA | BBA-6/RCA | BBA-0/RMA | BBA-3/RMA | BBA-6/RMA |
|---|---|---|---|---|---|---|---|---|---|---|
| Water penetration (mm) | 28 | 36.3 | 61.5 | 75.3 | 65.5 | 79.3 | 102.6 | 70.7 | 86.7 | 112.6 |
| Chloride penetration (mm) | 28 | 10.3 | 19.7 | 21.8 | 15.3 | 21.1 | 22.2 | 19.9 | 22.5 | 24.1 |
| | 56 | 18.1 | 23.1 | 27.2 | 21.9 | 26.9 | 31.2 | 22.4 | 27.7 | 32.5 |

Regarding the concrete with RA and BBA, the water penetration was higher. However, the increase was a proportionally lower penetration compared to similar concretes with 0% of BBA (an average of approximately 21% and 48% for the 3% and 6% replacement rates).

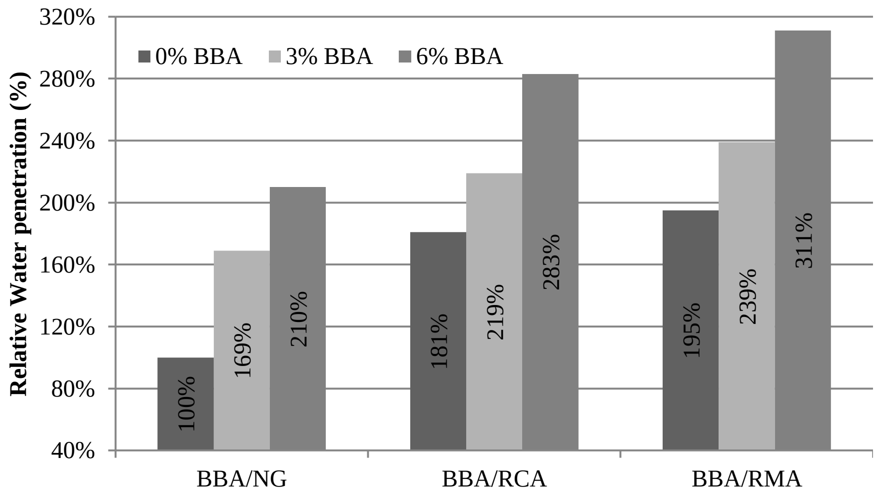


**Figure 9.** Comparison of water penetration at 28 days with respect to reference concrete (BBA-0/NG)

Mas et al. [5] concluded that the penetration of water under pressure increased upon the addition of mixed recycled aggregates with a high linear proportionality. This is inconsistent with the work of Martinez-Lage et al. [6], where water penetration was less with the incorporation of RMA.

### *Chloride ion penetration test*

Cylindrical specimens that were 50 mm (radius) x 200 mm (height) and cured for 28 days were used in this method. A layer of epoxy resin was applied to the lateral surfaces as waterproofing. Subsequently, the specimens were immersed in a solution of 20.000 ppm NaCl. This method is not is referred to any standard. However, it is based in Otsuki et al. (1993) [28], where the solution is applied as previously described.

The specimens were extracted from the solution at 28 days and 56 days of exposure and were divided into two sections using a splitting tensile (Brazilian method). Sections were impregnated with an $AgNO_3$ solution and the penetration depth was measured.

The results obtained after 28 days and 56 days for the penetration of chlorides are given in Table 6.

As occurred in the water penetration test under pressure, the penetration increased with the incorporation of RA (Figure 10). The increases were 49% for BBA-0/RCA and 93% for BBA-0/RMA.

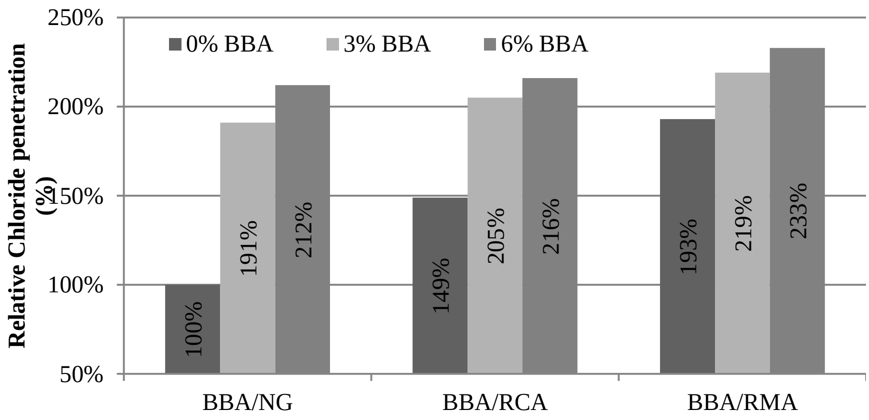


**Figure 10.** Comparison of chloride penetration at 28 days with respect to reference concrete (BBA-0/NG)

Furthermore, chloride penetration increased significantly with the addition of BBA (91% and 112% for the replacements of 3% and 6%) compared to BBA-0/NG.

In contrast, the chloride penetration increased to a lesser extent with the addition of the BBA in BBA/NG series respect to concretes with RA (38% and 45% for the BBA/RCA series and 13% and 21% for the BBA/RMA series). Therefore, the addition of BBA affected to a greater extent the concretes with RCA and RMA regarding BBA/NG concretes. Comparing the two properties related to the durability of concrete, Figure 11 shows the correlation between the penetration of water under pressure and chloride penetration.

Both properties were increased with the increased BBA for the three series of concretes manufactured. For all concretes, the chloride penetration increased proportionally to the penetration of water under pressure, and vice versa, whereby, both properties can be determined with high accuracy from another property.

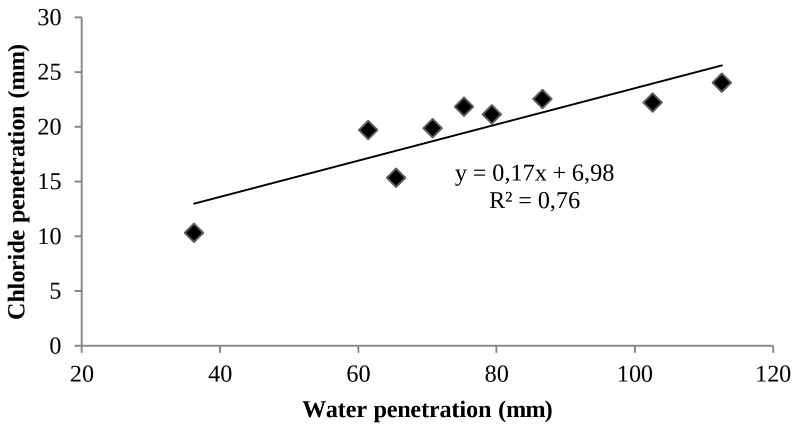


**Figure 11.** Correlation between chloride ion penetration and water penetration under pressure

### *Drying shrinkage test*

To study the durability of the concrete, drying shrinkage measurements were obtained on the concrete prisms measuring 100 x 100 x 500 mm, according to ASTM C157. The specimens were exposed to conditions of 50% relative humidity and 20°C and the measurements were taken for 1, 4, 7, 14, 28, 56, 90, 180 and 360 days.

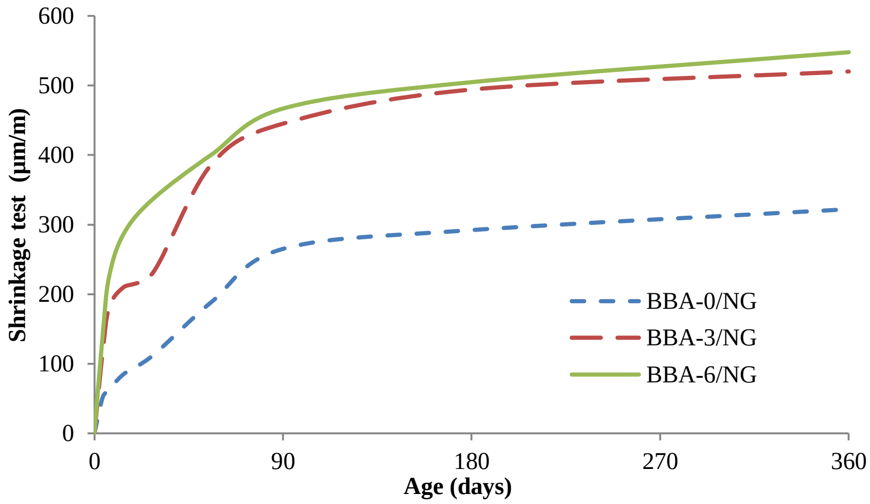


**Figure 12.** Evolution of shrinkage. BBA/NG series

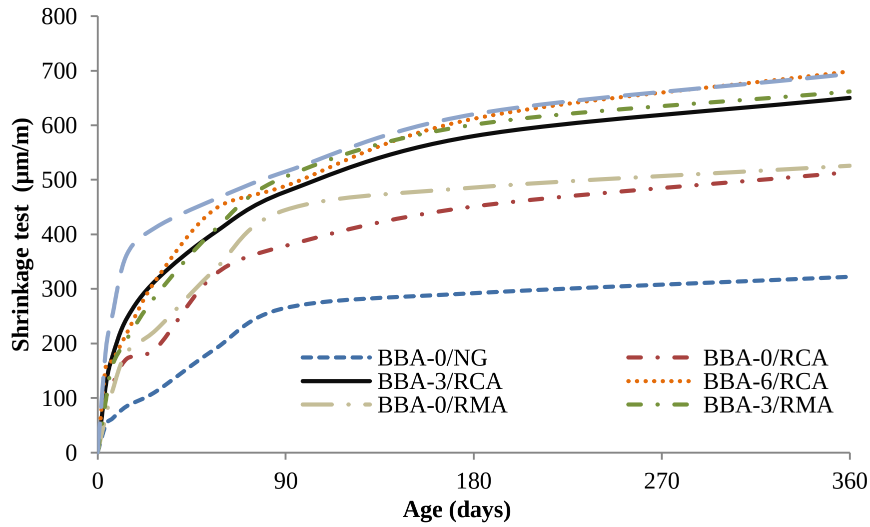


**Figure 13.** Evolution of shrinkage with respect to reference concrete (BBA-0/NG)

The results of the shrinkage test are shown in Table 6 and Figures 12–13. The concretes with a replacement of BBA had high shrinkage values. Similarly, the shrinkage values were higher in the BBA/RCA and BBA/RMA series compared to the control.

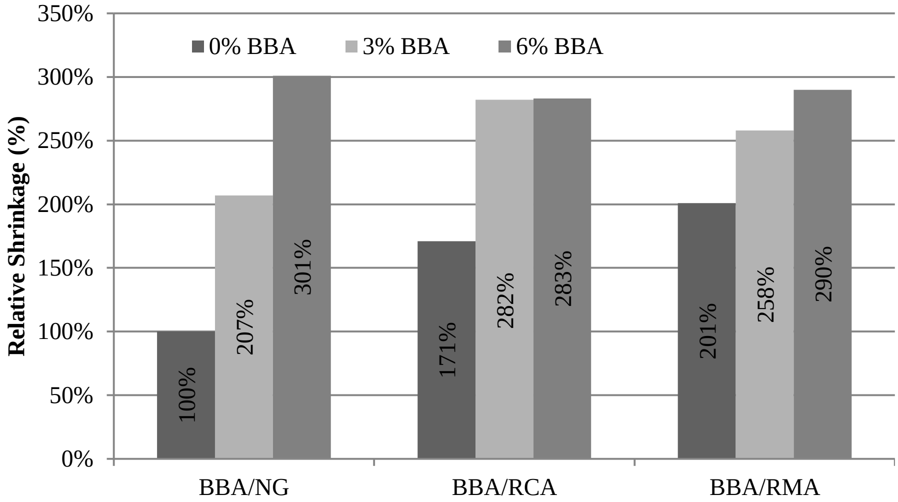


**Figure 14.** Comparison of shrinkage at 28 days with respect to reference concrete (BBA-0/NG)

The results agree with those obtained by Domingo Cabo, A., et al. [29], who asserted that the shrinkage increases with an increase in the amount of RCA and is significantly higher for a replacement rate of 100%.

## *Conclusions*

The following conclusions were obtained:

- The replacement of 100% NG by RCA and RMA provided compression and bending resistance that was lower than those obtained for the batch for all ages of the control measures.

- In turn, substituting NS for BBA values contributed to the compressive and bending strength's being significantly lower than the batches without replacements for all the BBA concrete produced.

- The replacement of NS by BBA resulted in a concrete with a lower density and higher absorption in the three series studied.

- Similarly, the replacement of 100% of NG by RCA and RMA impacted these properties, which were lower in all cases compared to the batch control.

- The penetration of water under pressure, chloride penetration and retraction were higher as they increased the rate of replacement of NS by BBA and RCA combined with RMA in the produced concrete, thereby incorporating the recycled aggregates. The BBA adversely affected the properties of durability.

In summary, the incorporation of RCA and RMA adversely affected the mechanical properties and durability of the produced concrete. However, the replacement of NG by RCA and RMA was 100%. Furthermore, the addition of the BBA replacement also resulted in a significant decrease in the mechanical properties and durability, which factors into the quality of the manufactured concrete.

Results showed that the absorption and density of the recycled aggregates (RCA, RMA and BBA) may be important to the durability of the produced concrete, which connects the absorption of the concrete with the properties analysed.

Therefore, it is advisable to use recycled concrete as both RCA and RMA at smaller replacement rates and to use recycled BBA concrete because the interaction between the recycled aggregates and BBA is more optimal than the combination of natural aggregates and BBA.

## *Acknoledgements*

The present work is a result of the project, the "PROPERTY STUDY FROM RECYCLED AGGREGATE AND RAP AND EB RCD, APPLICATION TO LINEAR INFRASTRUCTURE", conducted in cooperation with the Sacyr Building company and University of Cordoba, and is funded by the Ministry of Science and Innovation and the European Union through the "Operational Programme I + D + i by and for the benefit of businesses (Technology Fund)", and the European Regional Development Fund (ERDF) within the INNPACTO 2011 programme.

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# PUBLICACIÓN 4. PROPERTIES OF RECYCLED CONCRETE MANUFACTURING WITH ALL-IN RECYCLED AGGREGATES AND PROCESSED BIOMASS BOTTOM ASH

La cuarta Aportación, publicada en una revista indexada en el JCR, se corresponde con la Fase 4 descrita en la metodología que ha dado como resultado la publicación que se expone a continuación.

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ORIGINAL PAPER

## Properties of Recycled Concrete Manufacturing with All-in Recycled Aggregates and Processed Biomass Bottom Ash

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**Abstract** Recycled aggregates (RA) have been extensively studied in the production of concrete. Normally, the coarse fraction of recycled concrete aggregates (RCA) is the most commonly used to manufacture recycled concretes. The manufacturing of concrete with fine fraction of (NS) and improving the mechanical properties in concretes with low quantities of cement. It is possible to improve the properties of the BBA via mechanical processes (like screening or flotation) to reduce the organic matter content and there by obtain processed BBA (Pr-BBA). This study

## *Abstract*

Recycled aggregates (RA) have been extensively studied in the production of concrete. Normally, the coarse fraction of recycled concrete aggregates (RCA) is the most commonly used to manufacture recycled concretes. The manufacturing of concrete with fine fraction of RCA and/or recycled mixed aggregates (RMA) (from a mix of concrete, asphalt, masonry, etc.) has not been studied in depth. In most cases, the recycling plants produce RA with an ALL-IN particle size distribution. These recycled materials could be named as ALL-IN RECYCLED CONCRETE AGGREGATES (aiRCA) and ALL-IN RECYCLED MIXED AGGREGATES (aiRMA). Applying these aiRCA or aiRMA, limiting the percentage of the substitution of natural aggregates (NA) by the aiRCA, is more beneficial for both the production costs and the environment. In recent studies, other by-products, such as biomass bottom ash (BBA) were used in concretes, substituting natural sand (NS) and improving the mechanical properties in concretes with low quantities of cement. It is possible to improve the properties of the BBA via mechanical processes (like screening or flotation) to reduce the organic matter content and there by obtain processed BBA (Pr-BBA). This study provides interesting data on the mechanical and durability properties of the concretes manufactured with 30% aiRCA and aiRMA, and also by applying different replacement rates (0%, 15%, and 30%) of NA by BBA and Pr-BBA. The mechanical and durability properties were analysed over different time durations in different mixtures. It was demonstrated that it is possible to apply these recycled materials in non-structural concrete mixtures by limiting the replacement rate. The application of BBA and Pr-BBA reduced the properties of the concrete. However, this reduction was less significant with the use of Pr-BBA.

Keywords: all-in recycled aggregates, mechanical properties, recycled concrete, durability, biomass bottom ash

Acronyms: RA – recycled aggregates; RCA - recycled concrete aggregates; RMA – recycled mixed aggregates; FRA – fine recycled aggregates; aiRA – all-in recycled aggregates; aiRCA – all-in recycled concrete aggregates; aiRMA – all-in recycled mixed aggregates; C&DW – construction and demolition waste; BFA – biomass fly ash; BBA – biomass bottom ash; Pr-BBA – processed biomass bottom ash; OPC – ordinary portland cement; NA – natural aggregates; NCG – natural coarse gravel; NMG – natural medium gravel; NS – natural sand.

## *Introduction*

Several studies have been conducted to apply recycled aggregates (RAs) from old concretes or mixed demolition waste in roads, [1-3] mortars, [4,5] and concrete manufacturing [6-8]. A high proportion of recycled concrete aggregate (RCA) or recycled mixed aggregate (RMA) generated in plants are produced with a continuous particle size distribution and include fine and coarse particles (0-30/40 mm) [9]. This is known as all-in aggregate. These RAs can be referred to as all-in RCA (aiRCA) and all-in RMA (aiRMA).

The types of RA generally used in the manufacture of new concrete are normally processed by a screening procedure to separate the coarse particles from the fine particles. This allows us to use only the coarse fraction in the manufacture of recycled concretes and to eliminate the fine fractions of RCA [10,12] and RMA [13,14]. The fine fraction of the eliminated RA can be substituted for natural sand in the manufacture of concrete [15,16]. Evangelista and Brito [17,18] conducted several studies and showed that it is possible to incorporate up to 30% fine recycled aggregates (FRAs) in concrete. Due to the screening process, there is an increase in the price of the treatment to eliminate the fine fraction from the RA.

All-in recycled aggregates, such as the materials from construction and demolition waste (C&DW), are used in road bases or sub-bases, where a particle size distribution of 0-30/40 mm is needed. Several investigations have been performed using all-in granulometries of RCA and RMA in different road layers that were either treated with cement or left untreated [19, 20]. However, due to the limitation of using the fine fraction of RCA or RMA in the manufacture of concretes, the use of aiRCA/aiRMA has not been studied.

Furthermore, the bottom ash and the fly ash from the combustion of biomass are applied in construction areas [21-24]. However, the biomass fly ash (BFA) is often used in agriculture as a fertilizer due to its high potassium and nitrate content [24]. Generally, the biomass bottom ash (BBA) from calcined olive waste presents particle size distribution similar to natural sand. Therefore, these by-products can be used to substitute for natural sand in concrete and mortar. The BBA density is generally low due to the high particle porosity and the high organic matter content [25]. However, certain optimization methods (such as organics removal and grinding or extracting floating particles) could be applied to improve the properties of the BBA. The BBA could be improved by applying treatments such as screening or floating, thus yielding processed BBA (Pr-BBA).

In this paper, aiRCA and aiRMA mixed with BBA and Pr-BBA were applied to improve the environmental benefits and the technical implications in the manufacture of recycled concrete. The replacement rate of NA by aiRCA/aiRMA was 30%, and three percentages of BBA and Pr-BBA (0, 15 and 30%) substituting for natural sand were also applied. Fifteen concrete mixtures were prepared to study the mechanical and the durability properties of the hardened concrete mixtures.

## *Materials*

### Cement

As per the ASTM C150 standard, ordinary Portland cement (OPC) type CEM-I 52.5-R (rapid hardening) was used in this research. The properties of the cement are summarized in Table 1. The Valderrivas Portland Cement Company (Seville, Spain) supplied cement with a low $Al_2O_3$ content. This characteristic reduces the possibility of instability through shrinkage in concrete mixtures [26].

**Table 1**. Properties of cement

| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $K_2O$ | Density | Loss of ignition |
|---|---|---|---|---|---|---|---|---|
| % | % | % | % | % | % | % | (g/cm$^3$) | % |
| 19.58 | 4.41 | 2.5 | 64.18 | 0.94 | 3.37 | 0.93 | 3.15 | 1.44 |

### Natural Aggregates

Three types of NA from Villanueva de la Serena (Badajoz) were used. They include natural gravel (NCG), with a nominal particle size of 16-32 mm, natural medium gravel (NMG) with a nominal particle size of 4-16 mm, and natural sand (NS) with a nominal particle size of 0-4 mm. The particle size distributions are shown in Figure 1, and the physical and chemical properties are summarized in Table 2.

**Table 2.** Properties of the recycled and natural aggregates

| Properties | | NCG (16/32mm) | NMG (4/16mm) | NS (0/4mm) | aiRCA (0/32mm) | aiRMA (0/32mm) | Standard Test |
|---|---|---|---|---|---|---|---|
| Particle Size Distribution (% Passing) | 32 | 100 | 100 | 100 | 100 | 100 | EN 933-1 |
| | 16 | 4.3 | 100 | 97.6 | 95.45 | 84.41 | |
| | 8 | 0.1 | 100 | 31 | 73.13 | 68.33 | |
| | 4 | 0 | 89.5 | 1.02 | 56.21 | 46.45 | |
| | 2 | 0 | 78.51 | 0.4 | 42.11 | 32.12 | |
| | 1 | 0 | 60.13 | 0.39 | 31.55 | 20.05 | |
| | 0.05 | 0 | 37.04 | 0.38 | 20.43 | 12.1 | |
| | 0.025 | 0 | 15.19 | 0.4 | 10.66 | 3.2 | |
| | 0.0125 | 0 | 5.07 | 0.04 | 3.04 | 1.51 | |
| | 0.063 | 0 | 1.19 | 0.34 | 1.51 | 1.12 | |
| Composition | Rc (Crushed Concrete Particles) | - | - | - | 57 | 35 | EN 933-11 |
| | Ru (Natural particles) | 100 | 100 | 100 | 38.2 | 38 | |
| | Rb (Brick) | - | - | - | 4.5 | 26 | |
| | X (Others) | - | - | - | <1 | 1 | |
| Density-SSD ($kg/dm^3$) (0-4mm) | | - | - | 2.6 | 2.41 | 2.29 | EN-1097-6 |
| Absorption (%) (0-4mm) | | - | - | 1.21 | 6.81 | 9.87 | |
| Density-SSD ($kg/dm^3$) (4-32mm) | | 2.63 | 2.67 | - | 2.42 | 2.35 | |
| Absorption (%) (4-32mm) | | 0.86 | 1.3 | - | 5.05 | 8.56 | |
| Los Angeles abrasión value (AIM) (%) | | - | 28 | - | 36 | 39 | EN-1097-2 |
| Friability ratio (%) | | - | - | 11 | - | - | EN-83-115 |
| Sulphur content (%$SO_3$) | | <0.01 | <0.01 | <0.01 | 1.22 | 0.95 | EN 1744-1 |
| Soluble sulphate (%$SO_3$) | | <0.01 | <0.01 | <0.01 | 1.1 | 0.78 | |
| Chlorides (%) | | 0.06 | <0.01 | <0.01 | 0.0015 | 0.02 | |
| Organic matter content (%) | | <0.1 | <0.1 | <0.01 | | <0.01 | |

## All-In Recycled Aggregates

Several dosages of recycled materials were used in concrete manufacturing. All-in recycled aggregates (aiRAs) are used applying the fine and coarse fractions of the recycled aggregates. They are the most common and cheapest recycled materials obtained from the treatment of construction and demolition waste (C&DW). The aiRA are usually applied in road bases or subbases. It is necessary to separate the coarse fraction (>4 mm) in order to use these materials in non-structural concrete manufacturing. Conversely, previous studies have demonstrated that the FRA can be used in concrete manufacturing by limiting the percentage of FRA replacement. Evangelista and Brito [27] recommend using to a 30% replacement rate of FRA in concrete. This results in a 20% reduction in the compressive strength.

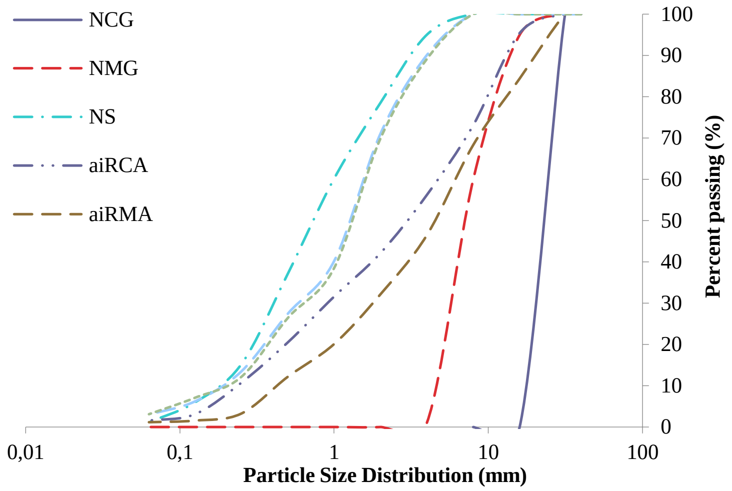


**Figure 1.** Particle size distribution

In this work aiRAs were applied by calculating the exact dosages of the mix of the fine and coarse particles, and limiting the sulphate content and the Los Angeles coefficient in the mixture. The use of FRAs increases the sulphate content compared to that of coarse recycled aggregates [28].

Two types of aiRA were used as follows:

All-in recycled concrete aggregate (aiRCA) from the treatment plant of ARISTERRA (Málaga), with the particle size limited to 0-20 mm.

All-in recycled mixed aggregate (aiRMA) from the treatment plant of GECORSA (Córdoba), with the particle size distribution limited to of 0-20 mm.

Due to the presence of adhered mortar in RCAs and the low density of brick fragments in RMAs, all natural aggregates present higher density values and lower water absorption capacity values than the recycled aggregates [39-31]. The aiRAs had lower values of the Los Angeles abrasion value due to the adhered mortar content and the weaker particle behaviour [29]. The values of the chemical properties of the natural aggregates were below the limit allowed by EHE-08. However, the values of the chemical properties of the recycled aggregates exceed the limits set by the EHE-08 [32]. For example, the BBA values are 0.23% for chlorides and 3.15% for organic matter content, and the aiRMA value is 1.1% for soluble sulphate due to the presence of particle ceramics [30].

Several studies have focused on the sulphate content in RAs. A high content (more than 1% in $SO_3$) can produce instability dimensions in the medium and long term and hence poses a problem in cement-treated materials such as soil cement or non-structural concrete. Conversely, all of the aggregates, including the recycled materials, show a continuous particle size distribution, ensuring a correct distribution of particles in the manufacture of concrete (Figure 1).

**Biomass Bottom Ash (unprocessed and processed)**

BBA from the thermal plant located in Linares, Jaen (belonging to "Industrial Sacyr Company") was used. These by-products have a nominal size between 0 and 4 mm. The particle size distribution is summarized in Figure 1, and the physical and the chemical properties are shown in Table 3.

This bottom ash is derived from the combustion of olive pruning used in the thermal power generation plant. The biomass combustion plants generate two types of waste, namely, BFA (biomass fly ash) and BBA [25]. BFA is obtained from the olive waste burned and is usually used in the agricultural sector owing to its superior fertilizer properties [21]. It is also occasionally used in the construction sector.

BBA contains unburned elements, light particles, and a high amount of organic matter. Previous studies have used BBA in the manufacture of concrete and mortar [23]. These by-products have high organic matter contents and a high percentage of light particles. In this paper, a laboratory treatment was used to reduce these two negative factors during the manufacture of recycled concrete. This process consisted of extracting the floating particles in a tank of water and thereby obtaining processed biomass bottom ash (Pr-BBA). The properties of these by-products are included in Table 3. According to the results listed in Table 3, BBA shows a high water absorption capacity and a low density. It also displays a high friability coefficient value, indicating that the BBA could experience mechanical attrition under loading.

Conversely, a high percentage of organic matter was detected in the sample collected from the power plant in Linares. It is important to note that this factor directly depends on the type of combustion system used at each power plant. The amount of organic matter present in the BBA is a consequence of the biomass combustion efficiency [33]. This percentage of organic matter decreases upon processing in the laboratory by floating. The results obtained for Pr-BBA were similar to the BBA results. However, due to the removal of the floating particles, Pr-BBA shows slightly higher density values, lower water absorption values and a lower amount of organic matter.

**Table 3.** Properties of Biomass Bottom Ash (BBA and Pr-BBA)

| Property | BBA | Pr-BBA | Standard |
|---|---|---|---|
| Density-SSD (kg/dm$^3$) (0-4mm) | 2.01 | 2.06 | |
| Dry Density (kg/dm$^3$) (0-4mm) | 1.71 | 1.72 | EN-1097-6 |
| Absorption (%) (0-4mm) | 20.03 | 19.1 | |
| Friability ratio (%) | 33 | 33 | EN-83-115 |
| Sulphur content (%$SO_3$) | 0.3 | 0.28 | |
| Soluble sulphate (%$SO_3$) | 0.28 | 0.23 | EN-1744-1 |
| Chlorides (%) | 0.23 | 0.23 | |
| Organic matter content (%) | 3.15 | 2.9 | |

**Water-reducing admixture**

A super-plasticizer (BASF Rheobuild 1222) was applied to improve workability in the recycled concrete. This super-plasticizer presents several properties, including reducing water content, reducing the w/c and improving the short-term strength of the concrete.

**Concrete mix proportions and manufacture of concrete**

Fifteen concrete samples were manufactured to study the mechanical and the durability properties. Three types of recycled aggregates were used for this, namely, aiRMA and aiRCA in coarse and fine fractions and BBA/Pr-BBA in fine fractions.

Due to the replacement of the NA by aiRCA/aiRMa, there are three groups of concrete, namely, the NA series, the aiRCA series and the aiRMA series. The replacement rates of NA by aiRCA/aiRMA were 30% by weight for both the coarse and the fine fractions. In each series, three replacement rates (0%, 15% and 30%) of the NS by the BBA were used. Additionally, identical concretes were manufactured using Pr-BBA instead of BBA. The mixed rates were obtained using the Bolomey method (Table 4 and Figure 2).

The w/c rate was 0.6 for all of the concrete. Due to the high absorption of aiRCA/aiRMA and BBA/Pr-BBA, a proportional amount of saturating water was added to each concrete to compensate the loss of the mixing water. With respect to the super-plasticizer, different amounts of saturating water were added in order to maintain a similar workability in all manufactured concretes. For this, previous studies were performed to determine the correct amount of the super-plasticizer.

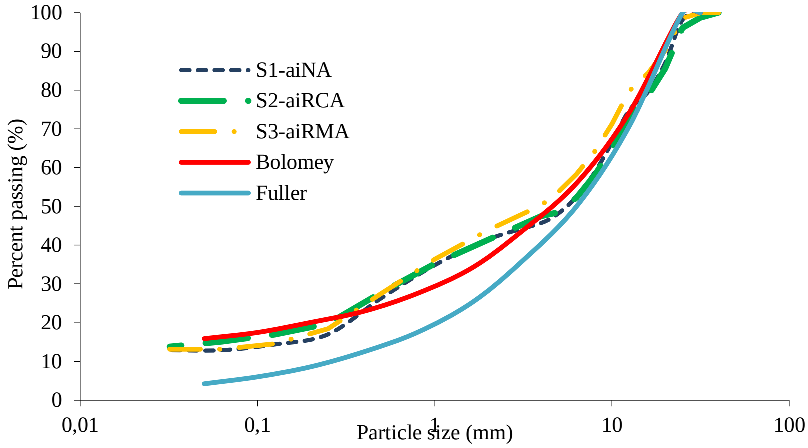


**Figure 2.** Particle size distribution in dosages

The recycled factor (RF) was calculated by applying the following expression:

$$RF = \frac{Recycled\ Aggregates + Biomass\ Ash\ (dry\ weight)}{Natural\ Aggregates\ (dry\ weight)} \cdot 10$$

The RF is calculated to compare the different properties in the concrete mixtures with the different contents of the recycled materials. A 50% replacement of NA by recycled materials (aiRCA or aiRMA and BBA or Pr-BBA) results in an

RF value of 10. The maximum RF value obtained in the mixes prepared in this study was 5.5.

**Table 4.** Concrete mix proportions (kg/m$^3$)

<table>
<tr><th rowspan="2">SERIE</th><th rowspan="2">MIX NAME</th><th colspan="3">NATURAL AGGREGATES</th><th colspan="2">RECYCLED AGGREG.</th><th colspan="2">BIOMASS BOTTOM ASH</th><th rowspan="2">CEM</th><th rowspan="2">Effec. Water</th><th rowspan="2">Sat. Water</th><th rowspan="2">Adm.</th><th rowspan="2">Total Weigth</th><th rowspan="2">Recycled Factor (RF)</th></tr>
<tr><th>NCG</th><th>NMG</th><th>NS</th><th>AI-RCA</th><th>AI-RMA</th><th>BBA</th><th>Pr-BBA</th></tr>
<tr><td rowspan="5">SERIE 1 – NA/BBA</td><td>CONTROL</td><td>480.6</td><td>707.5</td><td>834.6</td><td rowspan="5">0</td><td rowspan="5">0</td><td>0</td><td>0</td><td rowspan="5">275</td><td rowspan="5">165</td><td>0</td><td>2.7</td><td>2463</td><td>0</td></tr>
<tr><td>S1-NA/BBA15</td><td>480.6</td><td>707.5</td><td>709.8</td><td>81.6</td><td>0</td><td rowspan="2">12</td><td rowspan="2">4.1</td><td rowspan="2">2419</td><td rowspan="2">0.43</td></tr>
<tr><td>S1-NA/Pr-BBA15</td><td>480.6</td><td>707.5</td><td>709.8</td><td>0</td><td>81.6</td></tr>
<tr><td>S1-NA/BBA30</td><td>480.6</td><td>707.5</td><td>584.2</td><td>163.2</td><td>0</td><td rowspan="2">24</td><td rowspan="2">5.5</td><td rowspan="2">2376</td><td rowspan="2">0.92</td></tr>
<tr><td>S1-NA/Pr-BBA30</td><td>480.6</td><td>707.5</td><td>584.2</td><td>0</td><td>163.2</td></tr>
<tr><td rowspan="5">SERIE 2 – RCA/BBA</td><td>S2-aiRCA/BBA0</td><td>448.6</td><td>468.1</td><td>501.8</td><td rowspan="5">554.4</td><td rowspan="5">0</td><td>0</td><td>0</td><td rowspan="5">275</td><td rowspan="5">165</td><td>27</td><td>4.4</td><td>2413</td><td>3.9</td></tr>
<tr><td>S2-aiRCA/BBA15</td><td>368.5</td><td>481.3</td><td>478.4</td><td>57.8</td><td>0</td><td rowspan="2">36</td><td rowspan="2">10.3</td><td rowspan="2">2383</td><td rowspan="2">4.6</td></tr>
<tr><td>S2-aiRCA/Pr-BBA15</td><td>368.5</td><td>481.3</td><td>478.4</td><td>0</td><td>57.8</td></tr>
<tr><td>S2-aiRCA/BBA30</td><td>368.5</td><td>481.3</td><td>379.6</td><td>122.4</td><td>0</td><td rowspan="2">45</td><td rowspan="2">12</td><td rowspan="2">2348</td><td rowspan="2">5.5</td></tr>
<tr><td>S2-aiRCA/Pr-BBA30</td><td>368.5</td><td>481.3</td><td>379.6</td><td>0</td><td>122.4</td></tr>
<tr><td rowspan="5">SERIE 3 – RMA/BBA</td><td>S3-aiRMA/BBA0</td><td>387.2</td><td>465.5</td><td>564.2</td><td rowspan="5">0</td><td rowspan="5">535.9</td><td>0</td><td>0</td><td rowspan="5">275</td><td rowspan="5">165</td><td>45</td><td>3.8</td><td>2393</td><td>3.8</td></tr>
<tr><td>S3-aiRMA/BBA15</td><td>387.2</td><td>465.5</td><td>475.8</td><td>57.8</td><td>0</td><td rowspan="2">53</td><td rowspan="2">9.7</td><td rowspan="2">2362</td><td rowspan="2">4.4</td></tr>
<tr><td>S3-aiRMA/Pr-BBA15</td><td>387.2</td><td>465.5</td><td>475.8</td><td>0</td><td>57.8</td></tr>
<tr><td>S3-aiRMA/BBA30</td><td>387.2</td><td>465.5</td><td>377.0</td><td>122.4</td><td>0</td><td rowspan="2">63</td><td rowspan="2">11.2</td><td rowspan="2">2328</td><td rowspan="2">5.3</td></tr>
<tr><td>S3-aiRMA/Pr-BBA30</td><td>387.2</td><td>465.5</td><td>377.0</td><td>0</td><td>122.4</td></tr>
</table>

In the manufacturing process, the same method was used for all of the concretes. First, the coarse aggregates are introduced in the mixer. Then, the fine aggregates are introduced with 50% of the total amount of water (by mixing water and the absorption water) for five minutes. Second, the cement is added to the mixer with 50% of the total amount of water and the amount of super-plasticizer for an additional five minutes. After mixing the concrete, the slump value is measured. The process ends with mould filling and subsequent vibration on the vibrating table. Finally, the moulds are taken to a humidity chamber with a given temperature and humidity (20° and 100% relative humidity).

## *Experimental methods and results*

### Slump

To determine the workability of the fresh concrete, the Abrams cone method was applied according to EN 12350-2. All of the concretes display similar values, as the super-plasticizer additive was added according to the amount of BBA and Pr-BBA added (Table 6). This was because the concrete is more quickly matured in the presence of BBA. Conversely, incorporating aiRCA and aiRMA did not affect this property.

### Density and absorption of hardened concrete

The EN-12390-7 standard was applied on cubic samples with a length of 150 mm on day 28 to determine the density and the absorption of the hardened concrete (Table 6). Higher values of density were obtained by CONTROL. The incorporation of aiRCA and aiRMA resulted in a slight density decrease (an average of 1.6%) with respect to the CONTROL.

On the other hand, replacing the NS by the BBA/Pr-BBA led to lower densities compared with CONTROL. Similar results were obtained by *Beltrán et al. (2014)* [23], who obtained a density loss of 2.5% in concretes with the replacement of 6% of the NS by BBA. In the case of the incorporation of BBA/Pr-

BBA and aiRCA/aiRMA concretes, the higher the amounts of the BBA/Pr-BBA are, the lower is the obtained density.

The reduction in the density of concrete with aiRCA / aiRMA is due to the presence of the adhered mortar and ceramic particles [28-29]. Gonzalez and Etxeberría [34] obtained density loss of 1.2% for similar rates of replacement. Furthermore, due to the high porosity of the particles and the high organic matter content, the replacement of NA by BBA / Pr-BBA reduces the density of the concrete [23]. The density reduction is related to the loss of compactness and the quality of the concrete. The density may also be reduced by other properties such as the compressive and flexural strengths and the durability properties.

The CONTROL mix presented the lowest values of absorption. The water absorption capacity increases with the incorporation of BBA/Pr-BBA. The concrete mixtures with Pr-BBA presented lower absorption values than those with BBA, probably due to the absence of light particles.

Higher absorption values were obtained with the incorporation of aiRCA and aiRMA with respect to the CONTROL. Similarly, the absorption increased with the incorporation of BBA/Pr-BBA in the aiRCA and aiRMA series. That is, increasing the amount of BBA/Pr-BBA incorporated resulted in an increase in the absorption. The water absorption capacity was similar in both concretes with BBA and those with Pr-BBA. Hence, extraction treatment of the floating particles did not improve the water absorption capacity.

Other researchers, such as Thomas et al. [35], have observed increases in the water absorption capacity in the concretes with the RCA. Conversely, research has also shown increases in the absorption of the concretes with the BBA with respect to the reference concretes [23]. A high absorption in the concrete is related to a lower compactness, and a higher recycled aggregate content can be related to a decrease in other mechanical and durability properties.

**Compressive strength**

The compressive strength was determined for six cubic samples of 100 mm for durations of 1, 7, 28 and 90 days according to EN 12390-3. Due to the rapid hardening of cement, significant increases in the compressive strength (79-93% of compressive strength at 28 days) in the first 7 days of age were obtained for all concretes. This agrees with similar results obtained by previous research [23,36].

Lower compressive strength values were obtained for the concrete made with the BBA/Pr-BBA with respect to the CONTROL. That is, the higher the incorporation ratio of BBA/Pr-BBA is, the lower are the compressive strength values (Table 5).

Compressive strength was significantly lower for aiRCA/BBA0 and aiRMA/BBA0 with respect to the CONTROL [13,37]. Additionally, the reduction of the compressive strength was more significant, potentially due to the high content of ceramic particles in the aiRMA.

With the incorporation of the BBA/Pr-BBA, lower compressive strength values were obtained in the aiRCA/aiRMA series. That is, the higher the replacement rate of NS by BBA/Pr-BBA is, the lower are the compressive strength values. However, concretes with Pr-BBA yielded better results when compared with the concretes with BBA. Hence, processing with Pr-BBA improves the properties of the concretes.

Due to the high porosity and high organic matter content, the incorporation of BBA/Pr-BBA reduces the compressive strength of the concretes. In a previous study, Beltrán et al. [23] observed a loss of compressive strength in concretes with

BBA, with a decrease of 15-20% in the compressive strength for replacement rates of 3-6% with respect to the reference concrete. Conversely, the presence of adhered mortar in aiRCA and ceramic particles in aiRMA decreases the compressive strength.

**Table 5.** Evolution of compressive strength.

| Compresive Strength (MPa) | | | | | |
|---|---|---|---|---|---|
| Time (days) | CONTROL | S1-NA/BBA15 | S1-NA/PrBBA15 | S1-NA/BBA30 | S1-NA/PrBBA30 |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 16.1 | 11.4 | 14.1 | 10.2 | 12.4 |
| 7 | 39.2 | 31.0 | 32.1 | 24.9 | 26.7 |
| 28 | 47.1 | 36.1 | 39.3 | 31.4 | 32.2 |
| 90 | 52.4 | 39.2 | 43.1 | 34.9 | 35.8 |
| Time (days) | S2-aiRCA/BBA0 | S2-aiRCA/BBA15 | S2-aiRCA/PrBBA15 | S2-aiRCA/BBA30 | S2-arRCA/PrBBA30 |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 15.3 | 12.6 | 15.7 | 10.1 | 11.5 |
| 7 | 35.3 | 29.6 | 31.3 | 25.2 | 27.1 |
| 28 | 42.8 | 35.2 | 38.1 | 29.7 | 32.0 |
| 90 | 47.3 | 37.8 | 41.9 | 33.1 | 36.6 |
| Time (days) | S3-aiRMA/BBA0 | S3-aiRMA/BBA15 | S3-aiRMA/PrBBA15 | S3-aiRMA/BBA30 | S3-aiRMA/PrBBA30 |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 15.2 | 14.0 | 17.3 | 9.4 | 11.0 |
| 7 | 31.7 | 30.5 | 31.8 | 25.2 | 28.0 |
| 28 | 38.4 | 34.2 | 36.3 | 27.7 | 31.6 |
| 90 | 42.7 | 36.7 | 41.7 | 30.0 | 36.2 |

The density of the hardened concrete is related to the quality of the concrete. Similarly, the density is also related to the compressive strength. For the three series of concretes, a reduction in the compressive strength is proportional to the reduction in the density (Figure 3).

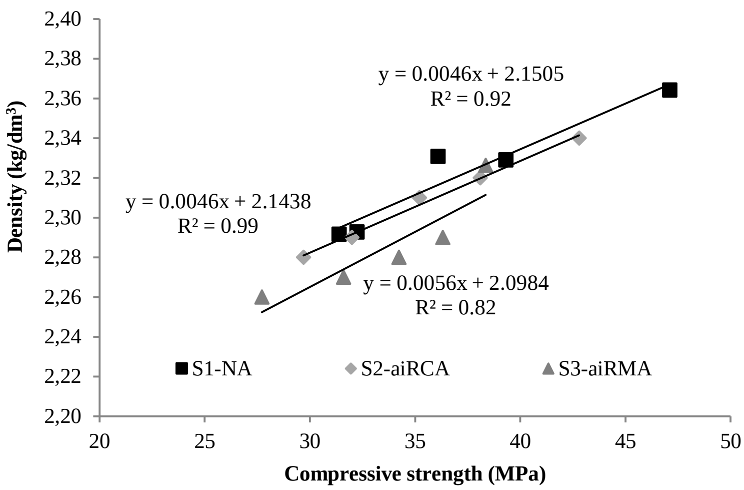


**Figure 3.** Relation between density and compressive strength

**Flexural strength**

For flexural strength, standard EN 12390-5 was applied to six prismatic specimens of dimensions 100 x 100 x 400 mm at 28 days of age. Lower flexural strengths were observed in the NA concretes with BBA and Pr-BBA with respect to the CONTROL. However, the differences between the 15-30% replacements were not very significant.

For aiRCA/BBA0 and aiRMA/BBA0, lower flexural strengths were obtained with respect to the CONTROL. However, the reductions were not significant. This is similar to the results of other researchers who have not observed significant flexural strength losses in the recycled concretes [38-39].

The concretes with aiRCA and aiRMA also present lower strengths upon incorporation of BBA/Pr-BBA. However, it should be noted that the values of BBA/Pr-BBA in the aiRCA and aiRMA series were similar to those in the NA series. There were no significant differences for this property between the concretes produced with BBA and those produced with Pr-BBA. The values obtained were essentially the same across the three series. That is, Pr-BBA does not improve the flexural strength.

As for compressive strength, the presence of adhered mortar and ceramic particles reduces the flexural strength, but this change is less significant than that of the compressive strength. Despite this, there is a good correlation between compressive strength and flexural strength (Figure 4).

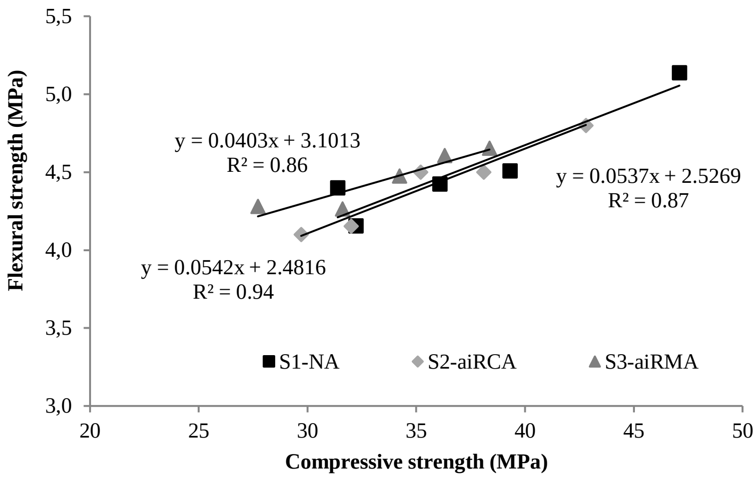


**Figure 4.** Relation between compressive strength and flexural strength.

**Ultrasonic Pulse Velocity**

Ultrasonic pulse velocity (UPV) was determined as an indirect method for compressive strength according to UNE EN 12504-4 at 1, 7, 28 and 90 days of curing (Table 6). As in the case of the compressive strength, the UPV values also increased with curing age. This is due to the solidification of the hardening of the concrete with curing age. Significant increases during the first 7 days of curing were observed for all of the concrete produced. After 7 days of curing, the increase in the UPV values was more progressive. This is in agreement with the findings of other researchers who also observed increases in the UPV values with curing age [40].

**Table 6.** Results of mechanical properties

| | | Workability (mm) | Compressive Strength (Mpa) | Flexural Strength (Mpa) | Density (Kg/dm³) | Absorption (%) | UPV (Km/s) |
|---|---|---|---|---|---|---|---|
| | AGE (Days) | 0 | 28 | 28 | 28 | 28 | 28 |
| SERIE 1 – NA/BBA | CONTROL | 9.0 | 47.1 | 5.1 | 2.36 | 6.8 | 4.51 |
| | S1-NA/BBA15 | 8.6 | 36.1 | 4.4 | 2.33 | 8.8 | 4.3 |
| | S1-NA/Pr-BBA15 | 8.9 | 39.3 | 4.5 | 2.33 | 8.5 | 4.33 |
| | S1-NA/BBA30 | 8.0 | 31.4 | 4.2 | 2.29 | 9.4 | 4.26 |
| | S1-NA/Pr-BBA30 | 8.9 | 32.2 | 4.2 | 2.29 | 8.9 | 4.27 |
| SERIE 2 – RCA/BBA | S2-aiRCA/BBA0 | 9.1 | 42.8 | 4.8 | 2.34 | 7.8 | 4.41 |
| | S2-aiRCA/BBA15 | 8.4 | 35.2 | 4.4 | 2.31 | 9.6 | 4.30 |
| | S2-aiRCA/Pr-BBA15 | 8.5 | 38.1 | 4.5 | 2.32 | 9.4 | 4.31 |
| | S2-aiRCA/BBA30 | 8.6 | 29.7 | 4.1 | 2.28 | 10.2 | 4.22 |
| | S2-arRCA/Pr-BBA30 | 8.4 | 32.0 | 4.2 | 2.29 | 10.0 | 4.26 |
| SERIE 3 – RMA/BBA | S3-aiRMA/BBA0 | 8.5 | 38.4 | 4.7 | 2.33 | 7.6 | 4.34 |
| | S3-aiRMA/BBA15 | 8.6 | 34.2 | 4.5 | 2.29 | 9.7 | 4.28 |
| | S3-aiRMA/Pr- | 8.7 | 36.3 | 4.6 | 2.29 | 9.2 | 4.29 |
| | S3-aiRMA/BBA30 | 9.0 | 27.7 | 4.2 | 2.26 | 10.0 | 4.20 |
| | S3-aiRMA/Pr- | 8.9 | 31.6 | 4.2 | 2.27 | 10.1 | 4.21 |

Lower values of the UPV were obtained for the NA series when the replacement rate of NS by BBA/Pr-BBA was higher. The UPV loss was higher when the replacement ratio was higher. On the other hand, the concrete with Pr-BBA outperformed the concrete with BBA.

In the aiRCA and aiRMA series, the UPV decreased with decreases in the aiRCA and aiRMA. Other researchers observed declining UPV values with the addition of RA [36, 40]

When15-30% BBA/Pr-BBA was incorporated in the concretes with aiRCA and aiRMA, the strength loss was slightly less than that of the concretes without

BBA and Pr-BBA. In this case, the influence of BBA is not different from the influence of Pr-BBA.

As the UPV is related to the hardened concrete quality, a relationship exists between the compressive strength and the UPV values (Figure 5). An appropriate non-destructive test can estimate the compressive strength vs. UPV relationship for the three series. Other researchers have also observed a similar relationship between the properties [40-41].

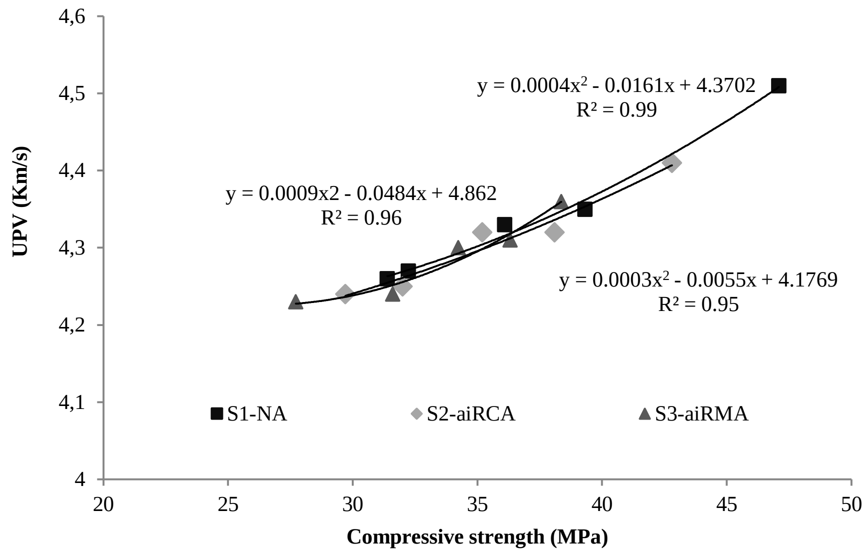


**Figure 5.** Relation between UPV and compressive strength.

**Penetration of water under pressure**

The penetration of water under pressure was measured at 28 days for the cylindrical specimens with mm-dimension D150 and G300 mm using UNE-EN 12390-8. The incorporation of BBA and Pr-BBA was allowed to obtain higher penetration values of water in the NA concretes with respect to the CONTROL. The penetration of water increased with the increases in the incorporation of BBA/Pr-BBA.

The penetration of water significantly increased with the addition of aiRCA and aiRMAwith respect to the CONTROL (Table 7). Conversely, the increases in the aiRMA series were higher due to the poor quality of the aiRCA, which contained a high content of ceramic particles. Correia et al. [42] confirmed the increased penetration of water in concrete with 30% ceramic particles.

In concretes with aiRCA/aiRMA and BBA/Pr-BBA, the penetration of water increased with respect to the CONTROL. The penetration of water increased with an increase in the replacement ratio of NS by BBA/Pr-BBA. Comparing the concretes with BBA and Pr-BBA, better results were obtained for the concretes with Pr-BBA than for the concretes with BBA.

**Table 7.** Durability properties of the concretes

| | | Penetration of water (mm) | Chloride difussion (mm) | Shrinkage (μm/m) |
|---|---|---|---|---|
| | AGE (Days) | 28 | 56 | 90 |
| **SERIE 1 – NA** | CONTROL | 41.6 | 41.8 | 232 |
| | S1-NA/BBA15 | 68.5 | 74.6 | 349 |
| | S1-NA/Pr-BBA15 | 61.4 | 70.1 | 329 |
| | S1-NA/BBA30 | 73.7 | 81.6 | 351 |
| | S1-NA/Pr-BBA30 | 64.7 | 79.9 | 349 |
| **SERIE 2 - RCA** | S2-aiRCA/BBA0 | 59.4 | 59.7 | 252 |
| | S2-aiRCA/BBA15 | 71.4 | 85.9 | 358 |
| | S2-aiRCA/Pr-BBA15 | 67.4 | 82.5 | 340 |
| | S2-aiRCA/BBA30 | 88.8 | 88.4 | 365 |
| | S2-arRCA/Pr-BBA30 | 80.7 | 86.1 | 345 |
| **SERIE 3 - RMA** | S2-aiRCA/BBA0 | 63.4 | 62.1 | 257 |
| | S2-aiRMA/BBA15 | 76.5 | 85.1 | 382 |
| | S2-aiRMA/Pr-BBA15 | 70.2 | 81.4 | 354 |
| | S2-aiRMA/BBA30 | 90.9 | 87.3 | 399 |
| | S2-aiRMA/Pr-BBA30 | 85.9 | 85.1 | 378 |

The penetration of water is related to the absorption of concrete. Both properties depend on multiple factors, including the porosity of the aggregates and the macropore volume [43]. Therefore, the higher porosity of aiRCA and aiRMA in conjunction with the high porosity of BBA / Pr-BBA are crucial for increasing the penetration of water. The relationship between the absorption of the hardened concrete and the water penetration is clearly defined. In all cases, the penetration increased with increasing water absorption, and hence, it can be stated that in this case, the water penetration increases with an increase in the absorption of concrete (Figure 6).

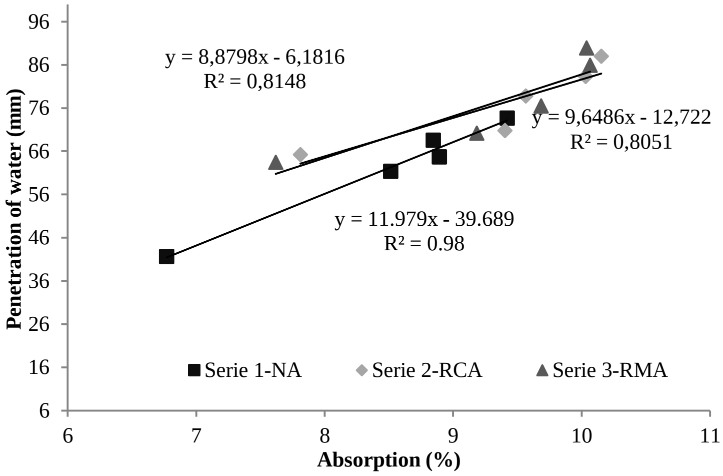


**Figure 6.** Relation between penetration of water and absorption

**Chloride diffusion test**

The chloride diffusion test was performed as per the ASTM C1202 standard at 56 days (Table 7). For the NA series, the values of the chloride diffusion test increased with respect to the CONTROL. Furthermore, the chloride diffusion test values increased as the replacement of NS by BBA increased.

With respect to the influence of RAs on concrete manufacturing, the chloride diffusion test values increased in the aiRCA and aiRMA series with respect to the CONTROL. As with the case of the NA series, the chloride diffusion test values increased with the increase in the replacement ratio of NS by BBA/Pr-BBA. Similar results were obtained for the concretes with both BBA and Pr-BBA. Therefore, the property did not improve with BBA processing.

As with the other properties, the chloride diffusion test value depends on the compactness of the concrete, which is related to the aiRCA and aiRMA quality. Due to their high porosity and a high content of organic matter, BBA and Pr-BBA are influenced by a loss in the quality of the concrete.

Zhang and Zong [44] observed slight increases in the chloride diffusion at an incorporation rate of 30% of RA. Meck and Sirivivatnanon [45] showed that high-quality concretes obtain lower values of chloride diffusion. This is inconsistent with this study, where higher values were obtained for the chloride diffusion. However, this work assumes a 30% rate of incorporation of recycled aggregates (both coarse and fine). The chloride diffusion test gives better correlations of the chloride diffusion values with the water absorption values and therefore is more appropriate.

**Drying Shrinkage test**

According to ASTM C157, the drying shrinkage was measured for the prismatic specimens with sizes of 100 mm x 100 mm x 500 mm at 1, 4, 7, 28, 56, 90, 180 and 360 days (Figure 7). For the first 28 days, a large increase in the drying shrinkage was obtained for all of the concrete. After 28 days, the increased drying shrinkage was more progressive. After 180 days of age, the shrinkage can be considered constant. The shrinkage increased by 45% to 76% due to the incorporation of BBA and Pr-BBA with rates of 15-30% with respect to the CONTROL.

For the concretes with aiRCA and aiRMA, similar increases were obtained for aiRCA/BBA0 and aiRMA/BBA0. Furthermore, the influence of the BBA and Pr-BBA was more significant in the concrete with aiRCA and aiRMA with respect to the NA series. The Pr-BBA concretes yielded slightly better results. However, the reduction in the differences between the replacements of 15-30% of the NS by BBA is remarkable. Others researchers have observed higher values of shrinkage in the concretes with RAs with respect to the control mixture concrete [41, 46]. Adam et al. (2001) [47] attributed these findings to factors such as the flexibility of the aggregates in the increased shrinkage of the concrete. The replacement of the natural aggregates by recycled materials is directly related to the increase in the shrinkage values.

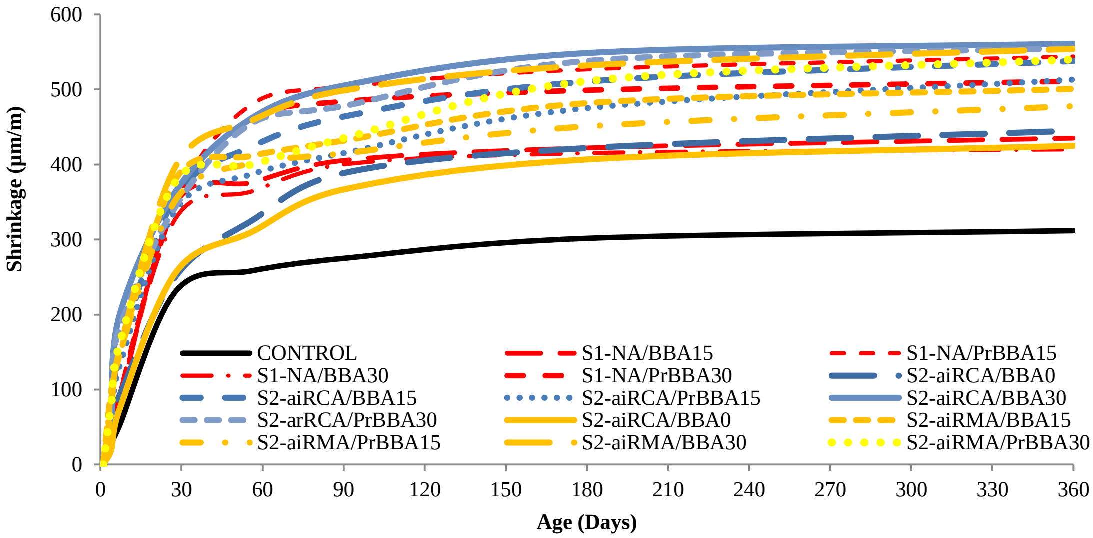


**Figure 7.** Relation between penetration of water and absorption

## *Conclusions*

Based on the results obtained, we present the following conclusions:

With respect to the physical and mechanical properties of the hardened concrete, incorporating 30% of the fine and coarse aiRCA and aiRMA, reduces the compressive strength and the flexural strength. This is due to the adhered mortar and the presence of ceramic particles in the RA.

Subsequently, the UPV values and the density are reduced in the presence of aiRCA and aiRMA, while absorption is enhanced in the concretes with the coarse and fine aiRCAs and aiRMAs. This is because the adhered mortar increases the porosity of the particles.

Similarly, the presence of BBA and Pr-BBA reduces the physical and mechanical properties of the manufactured concrete. However, the absence of light particles in the Pr-BBA optimizes the use of this residue in concrete. This leads to better results in the concretes with Pr-BBA than in the concretes with BBA.

With respect to the property of durability, the high absorption of aiRCA and aiRMA contributes significantly to reducing the quality of concrete, thereby obtaining higher values of water penetration, chloride penetration and chloride diffusion. The dry shrinkage is also increased in concretes with fine and coarse fractions of aiRMA and aiRCA.

As with the mechanical properties, the replacement of NS by BBA and/or Pr-BBA reduces the quality of the manufactured concrete, thereby contributing to the deterioration of the investigated durability properties. However, the deterioration of the durability properties is less significant in concretes with the residue without light particles (that is, Pr-BBA).

Despite the reduced quality of the concrete with the recycled aggregates, the concretes with the additions of the fine and coarse fractions of aiRCA and aiRMA with BBA and Pr-BBA show favourable results for use in certain situations, such as mass concretes or concretes with reduced specifications.

Additionally, it is advisable to process BBA by extracting the light particles to optimize its use in concrete manufacturing.

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CONFLICT OF INTEREST:

Francisco Agrela is a member of Committee "Technical Committee RAC: Structural behaviour and innovation of recycled aggregate concrete".

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The authors declare that they have no conflict of interest.

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# CAPÍTULO VII

## *CONCLUSIONES*

# CAPÍTULO VII

## *CONCLUSIONES*

Se exponen en este apartado las conclusiones derivadas de la investigación correspondiente a esta Tesis Doctoral, mostrándose con P1, P2, P3, y P4 la publicación correspondiente en cada caso:

- La utilización de CFB como sustituto de la arena no mejora el comportamiento mecánico de morteros reciclados en ningún caso de estudio. Por otro lado, la sustitución de cemento por CFB tampoco optimiza el comportamiento mecánico de los morteros (P1). Sin embargo, su influencia es menos negativa en este último caso, obteniéndose resultados similares para un 10% de sustitución respecto al mortero de control.

- Se demuestra que el comportamiento mecánico de morteros realizados con CEM-I y para reducciones del 10% de la arena normalizada es similar al obtenido por el mortero de referencia fabricado con CEM-II, permitiendo establecer una equivalencia entre ambos tipos. Sin embargo, este fenómeno no es demostrado para morteros con reducciones de cemento, donde la similitud entre ambos tipos de morteros es menos significativa (P1).

- La elevada porosidad de las CFB aumenta la porosidad y reduce la densidad de los morteros fabricados con las mismas. Este hecho queda demostrado tanto a nivel macroscópico (visible al ojo humano) como a nivel microscópico (P1).

- Se considera factible la posibilidad de sustituir arena por CFB en cantidades reducidas para la fabricación de morteros con CEM-I que no requieran exigencias técnicas elevadas (P1).

- La posibilidad de uso de AR aplicados como sustitutos de gravas naturales está ampliamente demostrada en investigaciones previas, a pesar de que, en general, la incorporación de más de un 20% de áridos reciclados reduce las propiedades mecánicas de los hormigones fabricados. Sin embargo, la incorporación de un máximo del 12% de cemento para tasas máximas de sustitución del 100% permite obtener resistencias a compresión similares a los hormigones de referencia, tanto para hormigones de baja resistencia característica, como hormigones de alta resistencia característica (P2). Asimismo, la resistencia a flexión aumenta con la incorporación de áridos reciclados y la adición de cemento, por lo que la influencia de los AR no afecta negativamente dicha resistencia en hormigones reciclados.

En cambio, no ocurre lo mismo con otras propiedades físico-mecánicas. La incorporación de áridos reciclados reduce la densidad y aumenta la porosidad de todos los hormigones fabricados a pesar de la adición de cemento, así como también reduce el módulo de elasticidad de los hormigones debido esencialmente a la presencia de mortero adherido. Por ello, se considera la posibilidad de emplear hormigones con áridos reciclados bajo la premisa de mantener la resistencia igual al hormigón de referencia bajo condiciones técnicas no exigentes (P2).

- La influencia de los AR reduce la calidad de los hormigones respecto a la durabilidad de los mismos en todas las propiedades analizas. El incremento de la tasa de incorporación de AR aumenta en todos los casos la penetración de agua, penetración de cloruros y la retracción sin excepción (P2). La reducción de calidad del hormigón reciclado en la durabilidad del mismo implica poder emplear su uso bajo condiciones ambientales no agresivas.

- La conjunción de AR, tanto de tipo mixto como de hormigón, en conjunción con CFB en hormigones reciclados, no ha sido anteriormente investigada. Es por ello que esta investigación también se centra en estudiar sus posibilidades de uso en hormigones de baja resistencia característica. Respecto a las propiedades mecánicas, la incorporación del 100% de áridos reciclados mixtos y de hormigón con CFB reduce dichas propiedades cuanto mayor es la tasa de incorporación de las cenizas: la resistencia a compresión y flexo-tracción sin más reducidas que las obtenidas para el hormigón de referencia. Sin embargo, esta reducción es más notable en el caso de hormigones con áridos reciclados mixtos (P3).

- La presencia de AR como la de CFB reduce otras propiedades físico-mecánicas y de durabilidad, como la densidad la cual se reduce, o la porosidad, la cual aumenta con la incorporación de áridos reciclados y cenizas. Propiedades de durabilidad como la penetración de agua, penetración de cloruros o retracción aumentan con la presencia de áridos reciclados, siendo ello un factor en contra del uso de este tipo de áridos reciclados (P3). No son estos hechos óbice para desechar el uso de ambos tipos de áridos. Se recomienda el uso de áridos reciclados tanto mixto como de hormigón, así como la incorporación de CFB como sustituto de AN en hormigones no estructurales de bajas exigencias técnicas y baja ambientes con condiciones no agresivas.

- La incorporación de un 30% de ARH y ARM en toda su fracción reduce las propiedades físico-mecánicas de los hormigones, siendo esta reducción más notable en la resistencia a compresión y menos significativo en otras propiedades como la resistencia a flexión y UPV. En el caso de la densidad y absorción, se reduje y aumenta respectivamente, aunque las variaciones son poco significativas (P4).

- En el caso de las propiedades mecánicas, la incorporación de un 30% de ARH y ARM reduce las propiedades de durabilidad, siendo este fenómeno más acentuado respecto a las propiedades mecánicas en propiedades como la penetración de agua y la difusión del ión cloruro. Sin embargo, en el caso de la retracción, ésta aumenta de forma menos significativa respecto de las dos anteriores propiedades (P4).

- De forma similar, la presencia de CFB tanto procesadas como sin procesar reduce las propiedades mecánicas y de durabilidad de los hormigones. Sin embargo, ya que la tasa de incorporación ha sido de hasta un 30%, es factible incorporar tasas de entre un 10-15% en hormigones que requieran exigencias técnicas reducidas (P4).

- Respecto las propiedades de hormigones fabricados con CFB procesada, la ausencia de partículas flotantes en las CFB procesadas optimiza el uso de este subproducto en hormigones ya que las pérdidas de calidad del hormigón son más reducidas, por lo que se recomienda su aplicación con procesamiento previo de las mismas (P4).

En general, el uso de AR reduce las propiedades mecánicas y de durabilidad de los hormigones fabricados con este tipo de residuos respecto al hormigón de referencia en prácticamente todos los casos. Sin embargo, este trabajo demuestra que una adición del 12% de cemento iguala e incluso mejora las resistencias a compresión y flexión.

Por otro lado, la incorporación de CFB reduce las propiedades mecánicas y de durabilidad en hormigones debido a su peor comportamiento como árido sustituto de la AN y a su no capacidad cementante como sustituto del cemento.

Por ello, la utilización de ambos tipos de residuos, tanto AR gruesos como CFB queda reducida a hormigones de exigencias técnicas reducidas y bajo condiciones ambientales no agresivas, siempre y cuando exista una adecuada supervisión técnica.

En cuanto a la posibilidad de efectos contaminantes de hormigones con áridos reciclados, este trabajo concluye que la utilización de los mismos para la fabricación de hormigones no repercute negativamente, siendo este tipo de hormigones inerte de cara al aspecto de impacto ambiental.

# CAPÍTULO VIII

## *BIBLIOGRAFÍA*

# CAPÍTULO VIII

## *BIBLIOGRAFÍA*


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# ANEXO I

*INDICIOS DE CALIDAD*

# ANEXO I

## INDICIOS DE CALIDAD

Se exponen en este apartado otros trabajos relacionados con esta Tesis Doctoral, llevados a cabo en el departamento de Ingeniería Rural de la Universidad de Córdoba y bajo la dirección de profesores de la Universidad de Córdoba.

La primera aportación, consistente en una publicación indexada en una revista de JCR, consistió en un estudio de comportamiento de lixiviación en hormigones para determinar su grado de contaminación bajo este proceso. Los resultados obtenidos fueron comparados con otras propiedades de los hormigones, como la absorción, densidad, resistencia o porosidad abierta.

La segunda publicación fue resultado de un trabajo de divulgación científica y fue publicado en una revista nacional. La investigación consistió en un estudio previo de comportamiento mecánico y de durabilidad en hormigones fabricados con sustitución de AN por CFB aplicando diferentes tasas de sustitución.

La tercera aportación es resultado de una investigación previa consistente en el análisis de la influencia de la materia orgánica en morteros fabricados con CFB. Los resultados fueron publicados y expuestos en un congreso internacional.

# APORTACIÓN 1. LEACHING ASSESSMENT OF CONCRETE MADE OF RECYCLED COARSE AGGREGATE: PHYSICAL AND ENVIRONMENTAL CHARACTERISATION OF AGGREGATES AND HARDENED CONCRETE.

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Leaching assessment of concrete made of recycled coarse aggregate: Physical and environmental characterisation of aggregates and hardened concrete

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## *Abstract*

Each year, millions of tones of waste are generated worldwide, partially through the construction and demolition of buildings. Recycling the resulting waste could reduce the amount of materials that need to be manufactured. Accordingly, the present work has analysed the potential reuse of construction

waste in concrete manufacturing by replacing the natural aggregate with recycled concrete coarse aggregate.

However, incorporating alternative materials in concrete manufacturing may increase the pollutant potential of the product, presenting an environmental risk via ground water contamination.

The present work has tested two types of concrete batches that were manufactured with different replacement percentages. The experimental procedure analyses not only the effect of the portion of recycled aggregate on the physical properties of concrete but also on the leaching behaviour as indicative of the contamination degree. Thus, parameters such as slump, density, porosity and absorption of hardened concrete, were studied. Leaching behaviour was evaluated based on the availability test performed to three aggregates (raw materials of the concrete batches) and on the diffusion test performed to all concrete.

From an environmental point of view, the question of whether the cumulative amount of heavy metals that are released by diffusion reaches the availability threshold was answered. The analysis of concentration levels allowed the establishment of different groups of metals according to the observed behaviour, the analysis of the role of pH and the identification of the main release mechanisms. Finally, through a statistical analysis, physical parameters and diffusion data were interrelated. It allowed estimating the relevance of porosity, density and absorption of hardened concrete on diffusion release of the metals in study.

## *Keywords*

Recycled concrete; Leaching behaviour; Heavy metals; Tank test; Diffusion; Physical parameters.


## *Introduction*

Nowadays, industrial by-products are widely used due to their ability to be recycled and valorised as secondary materials which allows at the same time saving natural resources and energy. Industries are finding new ways to use materials that would otherwise be discarded. Construction and industrial sectors are reusing waste materials in their own operations or applying them elsewhere for reusing as a substitute of raw materials. A successful example is the use of recycled aggregates from Construction and Demolition Wastes (CDW) in civil engineering works. The feasibility of use these materials in road construction have been proved by experimental projects performed by Pérez et al, 2013 (with cement-trated recycled material) or Jiménez et al, 2012 or Poon and Chang, 2006 (both studies focused on recycled aggregates as unbound road sub-base).

As a result, the valorisation of CDW is rising in value. However, during demolition, most materials are not separated, which is an essential step for achieving the concept of beneficial reuse. The main problem would be the use of construction materials that have been associated with toxic compounds as asbestos or lead-based paint. Sources as Del Rio et al., 2010 or Agamuthu, 2008 indicate that the mixture of inert and potential hazardous elements is a common practice during demolitions of building. Even the process operations performed by the CDW recycling plants can contaminate the product.

In that sense, Rodrigues et al, 2013 observed that the excessive light contaminants content on fine recycled aggregates could be caused by using low-tech separation equipments. In that sense, studies as Tiruta, 2013 have developed tools focused on identification of environmental hazards of concrete made using recycled aggregates. The most appropriate solution could be "designing for deconstruction", a concept that is becoming more fully recognised in this sector (Hao, 2008, Wang, 2010). This concept takes into account the potential reuse of materials by ensuring that buildings are designed and constructed so that materials can be more easily separated when buildings are dismantled. It implies that the generated construction waste should be sorted on-site before it is further processed (Hao, 2007, Olson, 2010).

From this framework, the present research work study analysed the potential reuse of CDW as a recycled aggregate (RA) in concrete manufacturing. First of all, it must be considered that the incorporation of alternative materials in the production of concrete is liable to increase the quantity of pollutant elements (as heavy metals) on the product (Marion et al., 2005). This fact could provoke an environmental risk due to the continued exposition of the contaminated concrete to the surroundings (Sani et al. 2005; Van der Sloot et al., 1996; Van der Sloot, 2000). This emphasises the need to analyse the leaching behaviour of these products.

Therefore, in the present study, not only the physical properties of different batches of hardened concrete were analysed, but also the leaching behaviour of the samples was evaluated. It will contribute to analysis developed by previous works regarding the environmental compatibility of construction materials manufactured with alternative products. Thus, it will be analysed the relationship between physical factors which affect directly to the contact degree between solid and aqueous phase (density, porosity and absorption of the hardened concrete) and the release of metals according to a diffusion leaching test.

The study is based on samples of hardened concrete manufactured with different replacement percentages of natural gravel by recycled concrete coarse aggregate. The analyses were performed for two types of concrete with different characteristic strength (HA-25 and HA-40) and the effect of the amount of recycled material on the physical behaviour of concrete was analysed. Secondly, to characterise the leaching behaviour of the concrete two tests were performed: the availability test for the detection of the fraction potentially available for leaching of the aggregates and the tank test for measuring the heavy metals that were released by diffusion (main mechanism of release in monolithic materials).

The results of both tests were superimposed in order to evaluate whether the cumulative amount of heavy metals reaches the availability threshold. Besides, the role of the pH was analysed for both leaching procedures which facilitated the identification of different groups of elements with similar behaviour. The present work also identified the main diffusion release mechanisms of the studied metals. Finally, a statistical analysis was performed for analysing the correlation between physical and leaching results, which allowed proving the relevance of density or absorption on the release.

## *Experimental procedure*

### *Characterisation of materials used for concrete mixtures manufacturation.*

### *Cement*

The present research was performed with Portland cement (PC) CEM I 42.5 R/SR which is defined according the UNE EN 197-1: 2000 standard. It is a pure grey cement clinker with a standard strength class of 42.5 and a rapid initial rate of strength development (UNE-EN 196-1: 1996). Moreover, the cement is sulphate-resistant, providing an improved durability for concrete in most aggressive environments and reducing the risk of structural deterioration. The chemical composition and main properties of PC are shown in Table 1.

**Table 1.** Composition and physical properties of the cement.

| Chemical composition (%) | | Physical properties | | |
|---|---|---|---|---|
| Calcium oxide (CaO) | 66.02 | Compressive strength: | | |
| Silicon dioxide ($SiO_2$) | 19.29 | Age (days) | 2 d | 28 d |
| Ferric oxide ($Fe_2O_3$) | 4.44 | Requirement (N/mm$^2$) | ≥20.0 | ≥42.5 & ≤62.5 |
| Sulfur trioxide ($SO_3$) | 3.29 | Mean value (N/mm$^2$) | 26.3 | 57.4 |
| Aluminium oxide ($Al_2O_3$) | 1.43 | Setting time: | | |
| Magnesium oxide (MgO) | 1.27 | Initial (min) | 167 | |
| Sodium oxide ($Na_2O$) | 0.09 | Final (min) | 222 | |
| Potassium ($K_2O$) | 0.34 | Expansion (min) | 0.46 | |
| Sodium oxide ($Na_2O$) | 0.31 | Fineness (% Rejection 32 µm): | 35 | |
| Chlorine (Cl) | 0.01 | | | |

*Fine and coarse natural aggregates (NS & NG)*

The natural aggregates used to manufacture the concrete mixtures had different origin: while sand came from a limestone quarry, the natural gravel was mainly composed by silica. Table 2 summarises their physical and chemical characterisation. Physical properties as water absorption and saturated surface dry density: SDD-Density (according to standard UNE-EN 1097-6: 2001), flakiness index (UNE-EN 933-3: 1997), Los Angeles (L.A.) coefficient (UNE-EN 1097-2: 2010) and friability coefficients (UNE 83-115: 1989), were measured. In addition, chemical properties as total sulphur, acid-solubles and chlorides (according to UNE-EN 1744-1: 1999) are included in the present study.

According to the data, as it is expected on natural aggregates, both NS and NG presented low water absorption and a high resistance to fragmentation (measured by the friability coefficient and the L.A. coefficient respectively).

**Table 2.** Physical and chemical properties of natural and recycled aggregates.

| Physical properties: | Natural sand (NS) | Natural gravel (NG) | Recycled concrete coarse aggregate (RCA) |
|---|---|---|---|
| Water absorption (%) | 1.03 | 1.53 | 6.95 |
| SSD-Density (g/cm$^3$) | 2.48 | 2.57 | 2.37 |
| Friability coefficient | 12.2 | - | - |
| L.A. Coefficient | - | 20 | 29 |
| Chemical properties: | | | |
| Total sulfur (% $SO_3$) | <0.01 | <0.02 | 0.96 |
| Acid-soluble sulphates (% $SO_3$) | <0.01 | <0.01 | 0.86 |
| Chlorides (%) | <0.01 | 0.10 | 0.03 |

Moreover, chemical tests detected despicable amounts of total sulphur, acid-soluble sulphates and chlorides in the natural gravel and sand. The higher levels of sulphates measured in the recycled material probably come from the mortar particles. As Sánchez et al. 2009 observed, mortar elevates the sulphate content on the recycled concrete aggregate because sulphate species originate during the addition of gypsum to the clinker.

Regarding size distribution of the materials, Figure 1 shows the notable differences in the grain size distribution between the natural sand (NS) and the coarser aggregate, the gravel (NG).

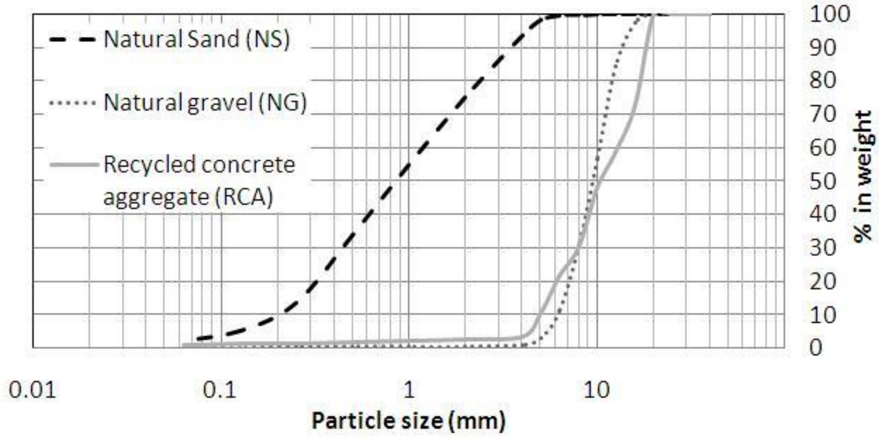


**Figure 1.** Granulometric curves of sand, gravel (NS, NG) and recycled concrete aggregate (RCA).

*Recycled concrete coarse aggregate (RCA)*

The recycled material used to replace the coarser fraction in the concrete mixture is a recycled coarse aggregate (RCA) composed mainly by concrete crushed and mortar and its composition (expressed in % in weight) is included Figure 2. This material was obtained by grinding concrete blocks and classified by a maximum size of 20 mm, as can be observed in its granulometric curve (see Figure 1). The grain size distribution of the RCA is similar to the gravel NG, which facilitated the replacement of the natural aggregate for the concrete mixtures preparation.

As a result, from the large concrete blocks present on the original CDW, a variable amount of mortar was produced in the samples of the recycled material and as a consequence, a poorer quality of the obtained RA. Its physical and chemical properties are shown in Table 2.

Unlike natural aggregates, RCA presented higher water absorption (a value of 6.95% while the natural materials presented water absorption levels of 1.03% for NS and 1.53% for NG). Additionally, RCA showed a higher L.A. coefficient proving less resistance than NS and NG which could be motivated by the remarkable presence of mortar in the RA. (Agrela et al., 2011, Sánchez de Juan y Alaejos, 2009).

Finally, regarding its chemical properties, despite the high levels of total sulphur measured in the sample, the RCA meet the limits set by the Spanish Technical Requirements for concrete (EHE, 2008). However, the content of acid-soluble sulphates is slightly higher than the limit value allowed by that regulation (0.8% $SO_3$ according to requirements of EHE-08).

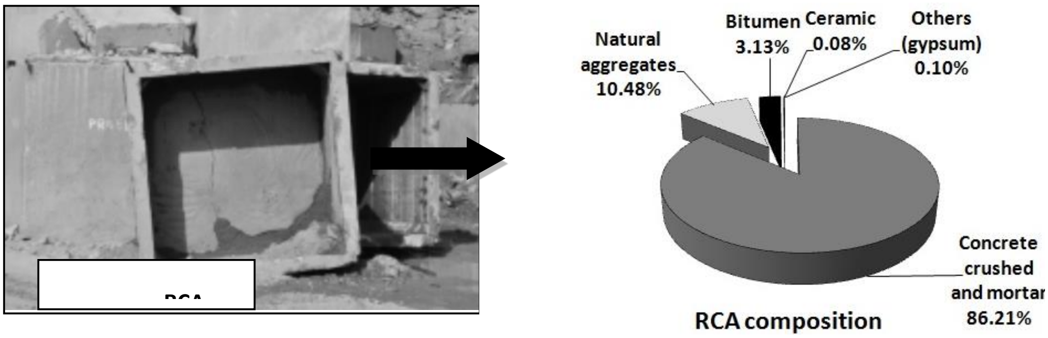


**Figure 2.** Composition of the recycled concrete coarse aggregate (RCA).

*Admixture for concrete*

The concrete batches were prepared by using a superplasticiser admixture supplied by the *BASF Group* (Rheobuild 1222). The admixture presents a density of 1190 kg/cm$^3$ at 20 ºC and a high water-reducing activity. It is specially designed for the concrete industry, characterised by a rapid evolution of mechanical strength at a young age.

*Concrete mixtures*

For the preparation of the concretes HA-25 and HA-40 (reinforced concrete with characteristic strength of 25 and 40 N/mm$^2$, respectively), PC, superplasticiser, fine and coarse aggregates were employed. During the laboratory procedure, some concrete mixtures were prepared by replacing the natural gravel (NG) with different portions of the recycled concrete coarse aggregate (RCA) to analyse the effect of the recycled material on its physical properties and leaching behaviour. Thus, as reference samples, H25-CONTROL and H40-CONTROL were prepared without replacement.

**Table 3.** Composition of concrete mixtures prepared for the laboratory study.

| | Proportions (kg/m$^3$) | | | | Replacement of RCA by vol. (%) |
|---|---|---|---|---|---|
| | Cement | NS | NG | RCA | |
| H25-CONTROL | 300 | 895 | 1052 | 0 | 0 |
| H25-G20 | 309 | 864 | 848 | 212 | 20 |
| H25-G50 | 320 | 818 | 538 | 538 | 50 |
| H25-G100 | 336 | 785 | 0 | 1060 | 100 |
| H40-CONTROL | 375 | 846 | 1020 | 0 | 0 |
| H40-G20 | 386 | 829 | 808 | 202 | 20 |
| H40-G50 | 399 | 795 | 504 | 504 | 50 |
| H40-G100 | 420 | 738 | 0 | 1014 | 100 |

The remaining concrete samples, both HA-25 and HA-40, were prepared with the following replacement percentages: 20%, 50% and 100%, as detailed in Table 3. It should be noted that 2 kg/m$^3$ of admixture was used for the HA-25 concrete batches and 3 kg/m$^3$ for the HA-40 batches. The effective w/c ratios were 0.60 and 0.5, respectively. The extra water absorption of the RCA (according to the values observed in Table 2) was taken into account during the concrete mixtures manufacturing and water was compensated following the mixing water compensation method developed by Ferreira et al, 2011.

***Test methods for physical characterization of hardened concrete***

The workability of the concrete was measured by the slump flow test according to the procedure described by the UNE-EN 12350-2: 2006. Density and porosity of the hardened concrete were evaluated following the methodology described by UNE-EN 12390-7: 2001. According to that, 150 mm concrete cube samples were prepared. Finally, the absorption test was conducted by immersion in a vacuum tank following the method proposed by CPC 11.3 (1994). This test is conducted at 28 days of age on cubic specimens of 150 mm.

***Leaching procedure for environmental assessment of concrete***

According to international experts, the leaching of compounds environmentally relevant from concrete samples is mainly controlled by diffusion mechanism (Marion et al., 2005, Van der Sloot and Dijkstra 2004, Hohberg et al., 2000; Hillier et al. 1999). Consequently, the most suitable procedure for laboratory simulation of on-site behaviour of hardened concrete is a tank leaching test.

Additionally, to assess the long-term environmental behaviour, it is necessary to determine the amount of heavy metals that are available for leaching

(Van der Sloot, 2000, De Groot et al., 1997). The Dutch standard extraction test (NEN 7341: 1994) determines the maximum leachability of an element due to the aggressive conditions imposed by this procedure (which simulates a worst-case scenario) (Van der Sloot, 2000, Pacheco, 2009). The test provides an upper limit of the leaching potential once the material is exposed in the field (Van der Sloot, 1998). Thus, pH during the test is altered at very low a level which provokes a higher release of certain metals (Townsend et al., 2003; Li et al., 2001; Galvín, 2012). Therefore, for the present study, the availability limit is used as threshold for the leaching data obtained by the diffusion test. An overview of both leaching procedures is summarised in Table 4 and a conceptual diagram about the materials tested by the experimental procedure is illustrated in Figure 3.

**Table 4.** Summary of the leaching procedures.

| | Availability test | Diffusion test |
|---|---|---|
| Standard | NEN 7341: 1994 | NEN 7345: 1994 |
| Samples | granular materials* | concrete cubes 100x100x100 mm |
| Materials tested | NS, NG and RCA | H25-CONTROL, H25-G20, H25-G50, H40-G100<br>H40-CONTROL, H40-G20, H40-G50, H40-G100 |
| Leachant | demineralised water | demineralised water |
| L/S ratio (V:V) | 50 | 5:1 |
| Number of steps | 2 | 7 |
| pH | 4 and 7** | Natural pH for all steps |
| Leaching periods | 3 h and 3 h | 0.25, 1, 2.25, 4, 9, 16, 36, 64 days |

*Footnote: (*) sample particle size is reduced to 125 µm. (**) pH is kept constant in each step by feed-back control and addition of* $HNO_3$

At the end of each normalised step, the eluate was separated, filtered (using a membrane filter of 0.45 µm) and stored for analysis. After that, leachates were analysed by inductively coupled plasma mass spectrometry (ICP-MS) using a Perkin Elmer ELAN DRC-e spectrometer. This analysis quantified the following heavy metals specified by the European Landfill Directive (Council Decision

2003/33/EC): Ni, Cr, Sb, Se, Mn, Hg, As, Pb, Cd, Cu, Ba and Zn. These elements were chosen for developing the present study due to the Landfill Directive is the only environmental regulation which is currently accepted by the Spanish Government. Thus, section 2 of this European Directive indicates the limit values of each of these metals for three different groups of wastes (inert, non hazardous and hazardous) according to their pollutant potential.

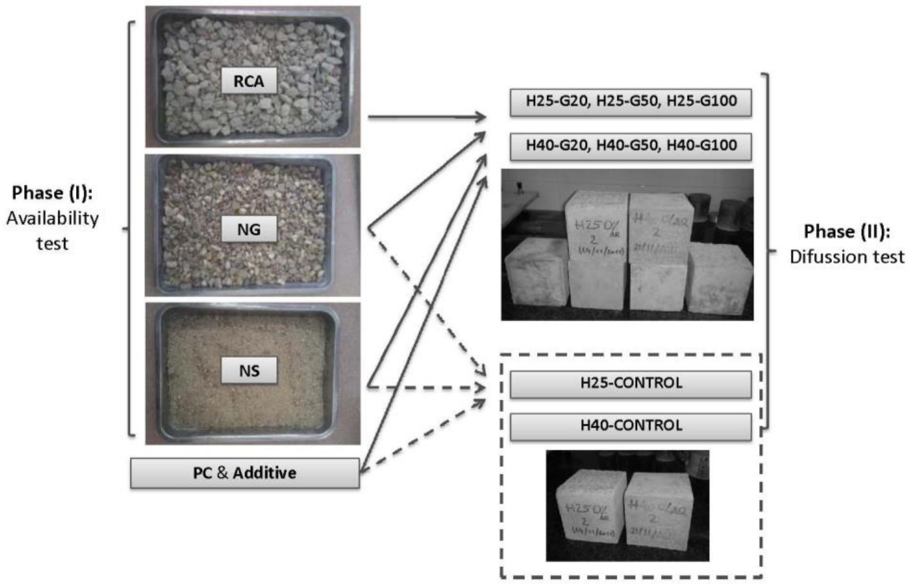


**Figure 3.** Conceptual diagram about tested materials during the experimental procedure.

## *Results and discussion*

### *Analysis of physical parameters of concrete batches*

*Slump*

To maintain the same consistency for all of the concrete batches (approximately 3.4 cm dry consistency), the water absorption by the aggregates during the manufacturing process was estimated. According to the obtained results, the slump did not vary significantly and an average value of 3.6 cm was obtained for both concrete batches, HA-25 and HA-40.

*Density and porosity of hardened concrete*

The European standard UNE EN 12390-7: 2010 for determination of density and porosity of hardened concrete recognizes three conditions or stages under which the mass of a specimen can be determined: a) as-received; b) water saturated and c) oven-dried. According to that, Table 5 shows three density values.

**Table 5.** Physical parameters of hardened concrete batches.

| | Density according to UNE EN 12390-7 ($kg/m^3$) | | | Porosity (%) | Vacuum absorption capacity (%) |
|---|---|---|---|---|---|
| | As-received | Water saturated | Oven-dried | | |
| H25-CONTROL | 2317 | 2347 | 2251 | 6.57 | 8.90 |
| H25-G20 | 2308 | 2334 | 2227 | 8.13 | 9.96 |
| H25-G50 | 2270 | 2293 | 2188 | 8.19 | 10.03 |
| H25-G100 | 2219 | 2245 | 2134 | 8.52 | 11.21 |
| H40-CONTROL | 2357 | 2373 | 2303 | 5.38 | 7.70 |
| H40-G20 | 2312 | 2332 | 2256 | 5.51 | 8.31 |
| H40-G50 | 2299 | 2320 | 2243 | 5.56 | 8.95 |
| H40-G100 | 2227 | 2246 | 2169 | 5.87 | 10.82 |

Thus, at 28 days of age after the curing of the concrete, specimens were extracted from the environmental chamber programmed at a temperature of 20 ºC and at a relative humidity of 100% (stage a). Later, samples were immersed in tank during 24 hours (stage b) and finally, concrete samples were dried at 105 ºC (stage c). The results are shown in Table 5 for the HA-25 and HA-40 concretes batches.

Figure 4 shows the evolution of density values (water saturated) and porosity for each concrete mixture prepared with different replacement rates. Trend lines of the data are represented with dashed lines.

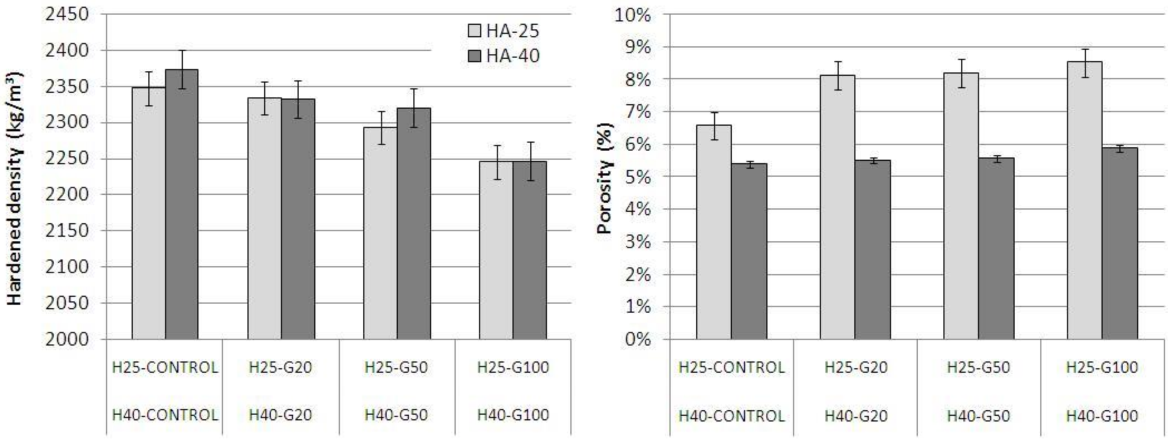


**Figure 4.** Evolution of water satured density and porosity according to replacement percentage.

According to the data, as it was expected, density decreased when the substitution rate of RCA increased for both concretes HA25 and HA-40, being more pronounced in the case of the HA-40 samples as it is observed in Figure 4. The effect of replacement percentage on density of hardened concrete has been previously studied by researchers as Matias et al. (2013) or Sanchez de Juan (2004).

These studies affirm that the differences in density values were affected by the density of the aggregates used in the concrete mixtures. It is corroborated by the data obtained in the present research. As it is showed in Table 2, the recycled aggregate (RCA) presented the lowest SSD-Density (2.37 g/cm$^3$). Therefore, it could explain that higher amounts of RCA in the concrete mixtures are causing lower density values in the hardened concrete samples.

The opposite trend was observed for porosity data, which increased for samples with higher replacement percentages. It is caused because the higher porosity of RA causes their particles are less dense and as a result, the density of the manufactured concrete decreases. (Tabsh et al, 2009, Etxebarría et al. 2006). Regarding a comparison between concrete types, the density obtained for HA-40 batches was slightly higher than the values of HA-25 samples due to the lower w/c ratio (0.5 for HA-40 and 0.6 for HA-25). Furthermore, the differences observed in porosity data were even greater.

*Absorption by immersion under vacuum.*

The water absorption of the hardened concrete batches was estimated according to the procedure described by CPC 11.3 and the results are showed in Table 5.

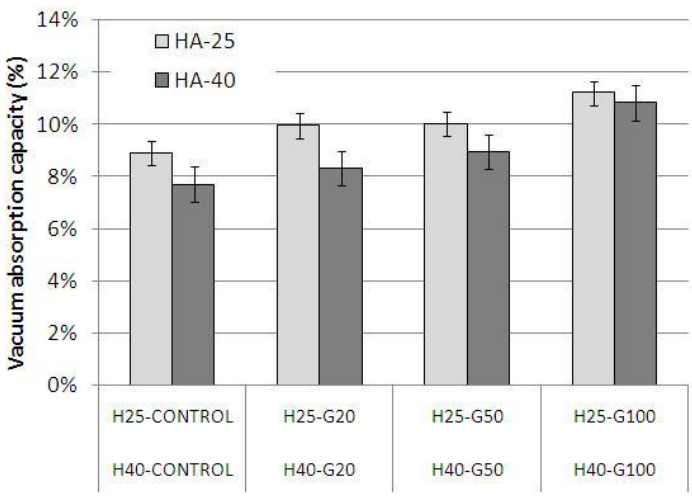


**Figure 5.** Evolution of absorption capacity according to replacement percentage

The influence of the vacuum conditions imposed by that procedure causes a high water absorption capacity in the material which provokes a lack of air particles in the pores and allowing a greater penetration of water. It was previously proved by Poon and Chan (2006) and Sagoe-Crentsil et al. (2001).

According to the data indicated in Table 5 and in Figure 5, a clear ascendant trend on the absorption capacity was observed when the replacement percentage increased. Furthermore, from the results it can be deduced that the percentage of water absorbed by HA-40 concrete batches was lower than the absorption produced by HA-25 samples.

***Leaching behaviour of legally regulated heavy metals***

*Interpretation of results from availability test.*

The concentrations of the heavy metals regulated by the European Landfill Directive were obtained by performing the availability test to the three granular materials used for preparing the concrete mixtures, and the results are showed in Table 6.

According to the data illustrated in Table 6, different response according to acid or neutral pH can be observed for two main different groups of metals: elements that uncertain conditions form oxyanions (Mo, Se, As, Sb and Cr) and typical metal cations (Zn, Cu, Ni, Pb and Cd).

Previous authors have performed in depth studies about the pH dependency of these groups of elements for recycled concrete aggregates (Engelsen et al. 2009, Engelsen et al., 2010). Therefore, based on these results, the different behaviour observed in the pH range of the availability test can be explained.

**Table 6.** Concentrations of heavy metals obtained by the availability test (NEN 7341: 1994).

| | Heavy metal concentration (mg/kg dry matter) | | | | | |
|---|---|---|---|---|---|---|
| | NS | | NG | | RCA | |
| | pH 7 | pH 4 | pH 7 | pH 4 | pH 7 | pH 4 |
| Mo | 0.13 | 0.11 | 0.09 | 0.01 | 0.39 | 0.06 |
| Se | 0.14 | 0.16 | 0.02 | 0.09 | 0.24 | 0.16 |
| As | 0.20 | 0.20 | 0.05 | 0.06 | 0.30 | 0.25 |
| Sb | 0.13 | 0.06 | 0.02 | < 0.001 | 0.24 | 0.16 |
| Cr | < 0.01 | 3.03 | < 0.01 | 0.15 | 0.06 | 3.72 |
| Zn | 0.59 | 8.52 | < 0.1 | 9.55 | 1.40 | 38.38 |
| Cu | 0.22 | 2.21 | 0.02 | 13.71 | 0.28 | 16.82 |
| Ni | 0.25 | 2.15 | 0.62 | 1.65 | 1.75 | 7.12 |
| Pb | < 0.005 | 0.05 | < 0.005 | 0.22 | < 0.005 | 10.67 |
| Cd | 0.002 | 0.117 | < 0.001 | 0.064 | < 0.001 | 0.212 |
| Ba | 5.40 | 40.55 | 32.12 | 54.14 | 14.12 | 35.80 |

*Footnote: Hg was negligible and inferior to the detection limit.*

This research study observed that cations as Zn, Cu, Ni, Pb and Cd present an increasing release pattern from the pH 7 to 4 which imply an increasing leachability in the acidic region. As a result, Table 8 shows that the release levels were higher at pH 4 (second step of the availability test) than at pH 7.

On the other hand, as Wahlstrom et al. (2009) exposed, the opposite behaviour is experimented by elements which form oxyanions such as As, Cr, Mo, Se and Sb. This group shows an increasing leachability at neutral o higher pH values which is corroborates by the higher release observed at pH 7 (Table 7).

Therefore, the availability data obtained by the present study corroborate the behaviour observed by these previous studies for both groups of pollutant metals.

In addition, the ability of materials to maintain a neutral or slightly alkaline pH level in the long term is very important due to leachability usually has a minimum within a specific pH range after which the release may increase or decrease. Thus, the acid neutralisation capacity (ANC) is a measure for the overall buffering capacity of a material against pH changes (Walhstrom et al. 2009). The ANC was determined by means of Equations 1 and 2 (according to standard NEN 7341: 1994) and the results are showed in Table 7.

$$ANC_7 = (V_1 \times C_1) \times f_2 / m_0 \qquad (1)$$

$$ANC_4 = (V_1 \times C_1 + V_2 \times C_2) \times f_3 / m_0 \qquad (2)$$

where: $ANC_7$ and $ANC_4$ are the acid neutralisation capacity of the material under investigation (at pH 7, and 4, respectively), expressed in mol/kg dry matter; $V_1$ and $V_2$ are the added volumes of nitric acid in the first and second steps of the availability test, expressed in ml; $m_0$ is the weight of the analytical sample, expressed in g; $C_1$ and $C_2$ are the molarities of the nitric acid added in the first and second steps ($C_1 = C_2 = 1$ mol/l); $f_2$ and $f_3$ are the conversion factors ($f_2 = f_3 = 1$ l x g/ml x kg).

*Footnote: $pH_A$: instantaneous natural pH after 1 minute; $pH_B$: stabilised pH after 10 minutes.*

The neutralisation reactions of acids (nitric acid in the case of NEN 7341: 1994) are typically associated with presences of basic calcium or magnesium compounds (Yan, 2007). Thus, carbonates such as calcite present a high neutralisation capacity due to they react neutralising acids quickly. In Table 7, the calcium contents (expressed in %) are included. The highest content of calcium was detected in the natural sand (24.8%) due to its mineralogical origin

(NS is a limestone sand while NG is a silica gravel) which is causing a more intense acid neutralisation (with values of $ANC_4$ = 9.52 and $ANC_7$ = 1.56).

As consequence, the natural sand presents a high ability to remain at stable leachability for most metals, followed by the RCA with values of $ANC_4$ = 4.06 and $ANC_7$ = 1.98.

**Table 7.** Acid neutralisation capacity (ANC) according to NEN 7341:1994 procedure.

| | Data from availability test | | |
|---|---|---|---|
| | NS | NG | RCA |
| $pH_A$ | 10.1 | 9.91 | 12 |
| $pH_B$ | 10.4 | 9.6 | 11.8 |
| $V_1$ (ml) | 25 | 10 | 32.5 |
| $V_2$ (ml) | 128 | 35 | 34.1 |
| $m_0$ (g) | 16.07 | 16.06 | 16.42 |
| $ANC_4$ (mol/kg dry matter) | 9.52 | 2.80 | 4.06 |
| $ANC_7$ (mol/kg dry matter) | 1.56 | 0.62 | 1.98 |
| Calcium at pH 4 (%) | 24.8 | 7.2 | 7.8 |
| Calcium at pH 7 (%) | 1.9 | 1.2 | 4.8 |

Finally, regarding the differences on availability leaching data between natural and recycled aggregates, as it was expected, due to the origin of the material the highest levels were released by the recycled material RCA for all metals regulated by the Landfill Directive.

***Leaching behaviour of hardened concrete batches. Diffusion test for monolithic samples***

In order to performing the Dutch tank test (NEN 7345: 1994), monolithic samples of concrete were prepared in the laboratory as follows: 100 mm cubes were cured for 56 days at 20ºC and > 90% RH. Then, all specimens were immersed in a given volume of demineralised water without acidification and kept in static conditions.

For this procedure, metal concentrations of the leachates are expressed in milligrams of element per surface unit (mg/m$^2$) as it is illustrated in Figure 6 and 7. The diffusion results are also expressed in Figure 9 as concentrations (mg/l). This data presentation facilitates the interpretation of specific aspects (e.g., evaluation of solubility control) and it enables the comparison of results for groups of constituents showing similar release behaviour (Van der Sloot and Dijkstra, 2004). In addition, leaching data in mg/l allows superimposing results from different procedures as diffusion test and availability data acting as threshold of leaching.

By means of the present study, all heavy metal regulated by the Landfill Directive were studied. However, only a representation of each group has been represented: Cr and Mo as representative of the group of metals which forms oxyanions, Zn and Cu as metal cations and the major compound: Ba. The different behaviour of each group (previously commented in availability section) is confirmed by the diffusion results. The different behaviour of metal cations and oxyanions is independent of the concrete type (HA-25 or HA-40) or the replacement percentage of natural aggregate.

Regarding the identification of the main release mechanisms, a slope of 1:0.5 is represented with the diffusion data in Figure 6 and 7. As Van der Sloot and

Dijkstra, 2004 affirm, pure diffusion-controlled release results in a slope of 0.5. Also other patterns can be observed as the depletion of mobile species (describing a flat line).

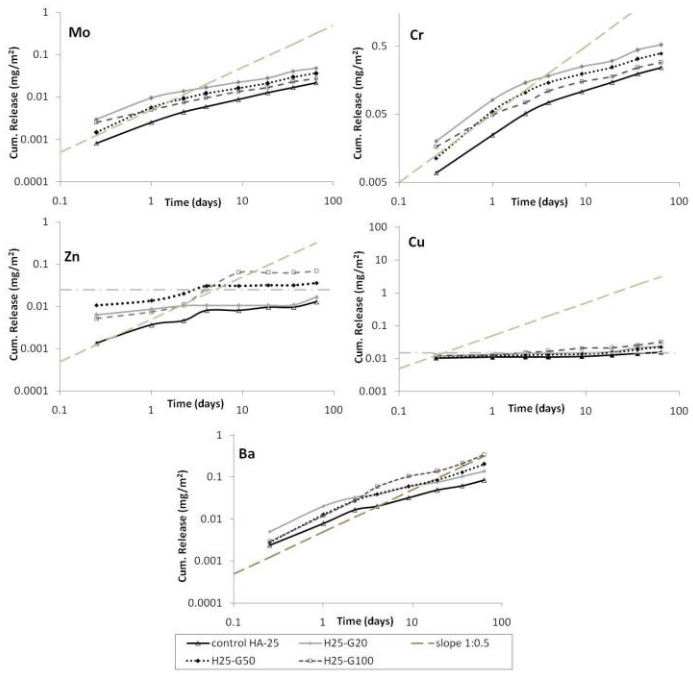


**Figure 6.** Diffusion test results for HA-25 concrete batches

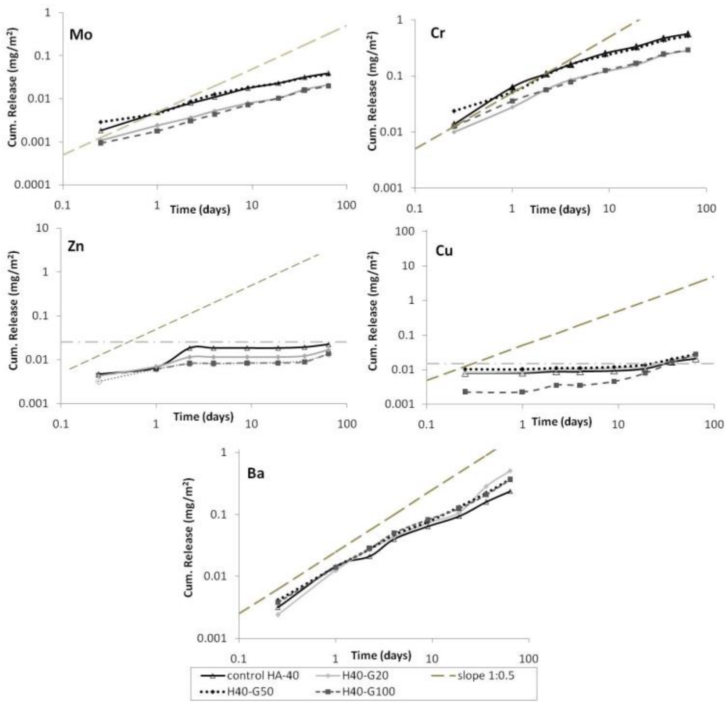

**Figure 7.** Diffusion test results for HA-40 concrete batches.

According to the represented data, the same release patterns were observed for both concrete types. The oxyanionic elements as well as the major element Ba were released by diffusion mechanism. However, metal cations as Zn and Cu (more mobile species) were released by different process.

The cumulative release curve of Zn during the first stages of the test describes a slope of 0.5, but from the fourth stage (2.25 days) the cumulative release is stabilized and the curve is transformed in a flat line (dashed and dotted line). In regard to Cu, the cumulative curve describes a flat line during the most of the test, indicating that a depletion of the soluble fraction is produced from the early stages of the test. Besides, it must be remarked that Cr and Mo also showed depletion from the ninth day of testing.

Once the main leaching mechanisms are identified for a representative group of the regulated metals, the differences observed for both concrete classes can be commented. The HA-25 concrete batches presented more marked differences depending on the replacement percentage. Thus, the sample CONTROL HA-25 (with 0% of replacement of natural aggregate) presented the lowest release levels for all metals represented in Figure 6. However, the highest amount of recycled aggregate in the sample H25-G100 (prepared with a 100% of replacement) did not imply the maximum release levels.

Regarding the HA-40 concrete batches, despicable differences were detected between the concrete batches manufactured with different replacement percentages. This is clearly observed on Zn, Cr and Ba. For explaining the differences between HA-25 and HA-40 samples it is necessary to analyse the pH data registered along the tank test, which are presented in Figure 8.

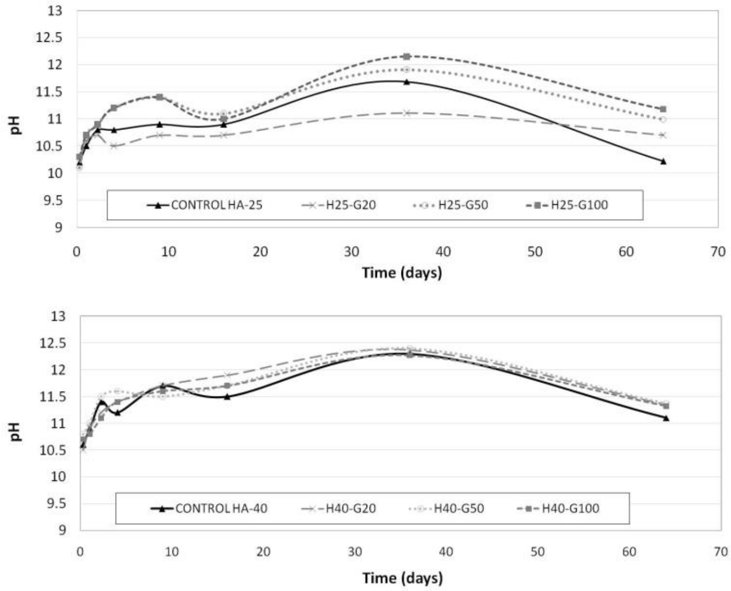


**Figure 8.** Evolution of pH data along the diffusion test for all hardened concrete samples

HA-40 samples showed despicable differences in the pH values registered along the diffusion test, which explains the lower differences observed in the release levels illustrated in Figure 7. Conversely, the higher variations on the pH values registered on HA-25 samples implied higher differences in the diffusion curves. Apart from that, a similar pH evolution for all the concrete batches manufactured was observed.

*Analysis about reaching the maximum leaching potential*

Once the availability and diffusion data have been discussed, the analysis for evaluating whether the maximum availability level is reached will be developed. The present analysis is focused on Cu, Zn, Mo, Cr and Ba in order to complete the analysis of their leaching behaviour. After confirming the highest pollutant potential of RCA compared to the natural aggregates, the RCA availability data are considered as threshold of leaching. Thus, these values are superimposed to the diffusion data of concrete manufactured with a 100% of replacement (H25-G100 and H40-G100).

Figure 9 represents the diffusion curves and the leaching thresholds designed as tZn, tCu, tCr and tMo.

The four values correspond to the highest concentration obtained by availability test. According to Table 6, concentration at pH 7 is chosen for Mo (more soluble at neutral pH as it was proved) while data at the acid pH of 4 are used for Cr, Zn and Cu. For achieve a consistent comparison (Van der Sloot and Dijkstra, 2004) all data represented in Figure 9 are expressed in concentration units (mg/l).

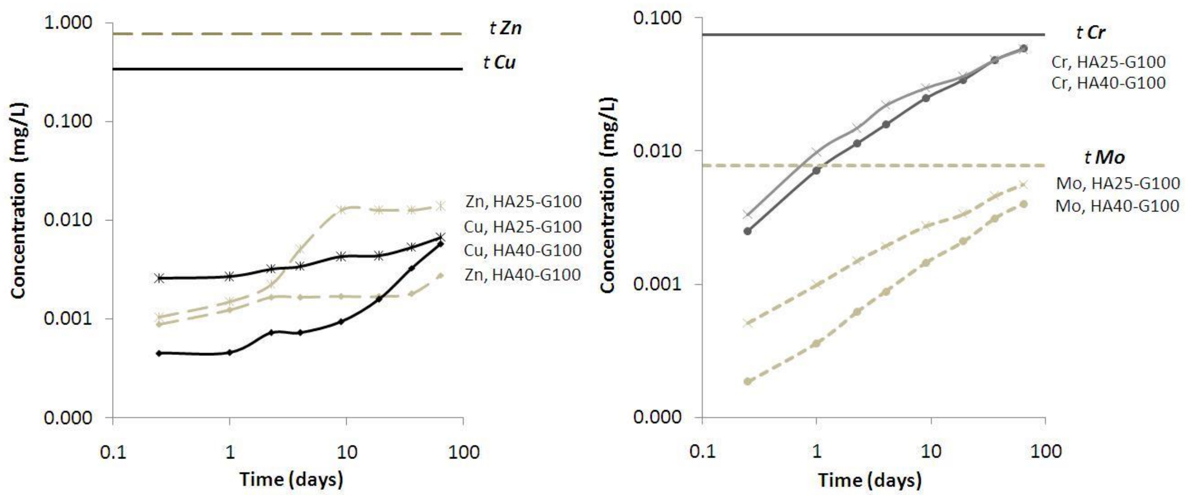


**Figure 9.** Diffusion curves and availability threshold for concrete manufactured with the maximum replacement percentage.

According to the data illustrated in Figure 9., similar results were obtained for both concrete types, and the different leaching behaviour of metal cations (Zn and Cu) and oxyanions (Cr and Mo) is again confirmed. While the threshold of the more mobile elements Zn and Cu is far from their diffusion curve, the last concentration of Mo and Cr is very close to the upper limits.

To explain the observed differences it is necessary to analyse again the role of the pH. Figure 8 showed the pH values registered during the diffusion test for all samples. The pH ranged between 10.5 and 12. According to previous studies as Engelsen et al. (2010) which analysed the pH dependency of trace elements in recycled concrete aggregates, Mo and Cr show a maximum of release in the alkaline pH range. However, Ni and Cu present a minimum on release levels for the same range of pH. Again, the role of pH on leachability of chemical species is essential to understand their leaching behaviour.

***Correlations between leaching and mechanical data.***

The present section analyses the correlation between release levels (expressed in $mg/m^2$) and physical factors which could affect directly to the permeability of the concrete (water saturated density, porosity and vacuum absorption capacity).

**Table 8.** Correlation between metals released by tank test and physical parameters. $R^2$ coefficients.

| | | Density SSD ($kg/m^3$) | | Porosity (%) | | Absorption vacuum capacity (%) | |
|---|---|---|---|---|---|---|---|
| | | HA25 | HA40 | HA25 | HA40 | HA25 | HA40 |
| Release ($mg/m^2$) | Zn | 0.98 | 0.57 | 0.46 | 0.49 | 0.83 | 0.53 |
| | Cu | 0.81 | 0.63 | 0.76 | 0.55 | 0.99 | 0.56 |
| | Mo | 0.02 | 0.45 | 0.30 | 0.42 | 0.03 | 0.33 |
| | Cr | 0.05 | 0.44 | 0.23 | 0.40 | 0.01 | 0.31 |
| | Ba | 0.98 | 0.08 | 0.60 | 0.04 | 0.91 | 0.02 |

The statistical analysis was performed with the metals listed in the Landfill Directive, but the in the present section, only the results obtained for the five elements in study are represented. Table 8 illustrates the $R^2$ coefficient for the mentioned elements, and Figure 10 shows the trend lines of metals which showed the highest correlation.

According to the data, the highest $R^2$ coefficients were obtained in the HA-25 concrete samples for the more mobile metals (Zn and Cu) and for the major element: Ba. The low $R^2$ values for Mo and Cr (ranged between 0.01 and 0.45) imply a non-significant statistical relationship.

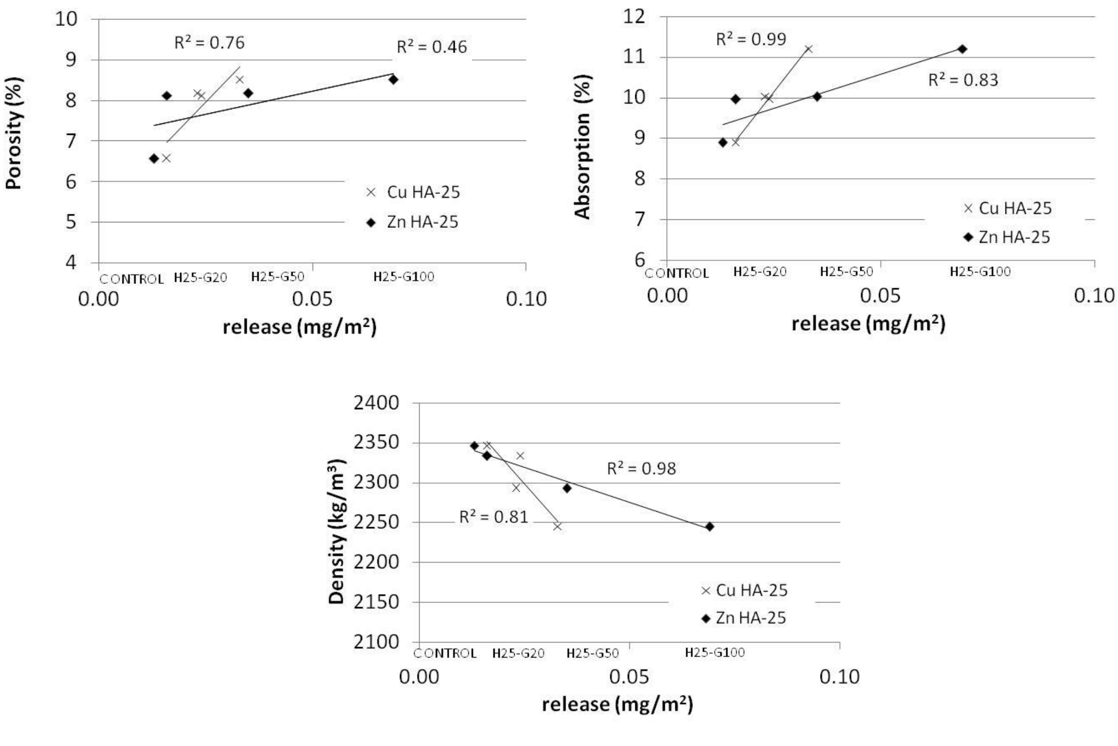


**Figure 10.** Trend lines which explain the relationship between release and physical data for Cu and Zn in HA-25 concrete samples.

The main goal of the present section is to estimate whether the relationship between physical parameters which affect to the release is strong or conversely, the parameters which intuitively increase the release (density, porosity and absorption) do not affect the leaching behaviour of concrete hardened. Figure A.1.10 represents the trend lines of elements that demonstrated a relationship moderately strong (Cu and Zn for HA-25 samples).

Trend lines show that the increasing of the percentage replacement of natural aggregate by RCA in concrete causes an increasing of porosity and absorption of the material. As a consequence, the higher contact solid-aqueous phase provokes a higher release of both mobile cations. This mobility is confirmed with the density-release graphic. The increasing of the percentage replacement (which causes a decreasing of density) also causes a greater release of Cu and Zn, as a consequence of the higher permeability. The high mobility of both elements has been previously discussed (Van der Sloot and Dijstra, 2004). Both elements (positively charged heavy metal cations, e.g. $Cu^{+2}$, $Zn^{+2}$) show high affinity for the adsorption to reactive surfaces (negatively charged) present in the material. The longer contact of material with the extractant phase (which occurs at conditions of high porosity, high absorption and low density) caused a greater release.

Regarding the remaining elements included in Table 8, their chemical nature and mechanisms that govern their release cause that the role of physical aspects are not very significant as compared to other more mobile species.

According to the statistical results and the low $R^2$ coefficient obtained it can be concluded that the role of density, porosity and absorption (which could affect directly to the permeability of the concrete) is not as relevant to the leaching behaviour as it was expected.

It can be explained because, apart from physical aspects, an important factor is governing the release: chemistry. It dictates the pore water composition that controls the trace elements leachability to a large extend (Van der Sloot et al., 1997). Therefore, not only physical parameters but also factors as pH of the solution are crucial parameters in the solubility the chemical species in study.

This reasoning confirms that the complexity of leaching process is difficult to reproduce and as Van der Sloot (1998) previously stated, not all the relevant aspects can be covered by test laboratory procedures which explains the non-significant statistical correlations obtained.

## *Conclusions*

As it was expected, higher RA content in the concrete mixtures caused lower density, higher porosity and higher absorption. Despite the outright differences in the physical response due to variations on replacement percentage, non-substantial differences were observed in the leaching behaviour of the different concrete mixtures, and the main conclusion are summarised below.

According to the availability test, two groups were identified: elements that uncertain conditions form oxyanions (Mo, Se, As, Sb and Cr) and typical metal cations (Zn, Cu, Ni, Pb and Cd).

While the levels released by the metal cations were higher at pH 4 than at pH 7, the group of oxyanions presented a high leachability at neutral pH values which is corroborates previous studies

From the analysis of the Acid Neutralisation Capacity it can be deduced that, due to the high content on calcium the natural sand (NS) presented the highest ability to remain at stable leachability for most metals, followed by the recycled material RCA.

By means of comparing the availability data between natural and recycled aggregates, it can be concluded that, as it was expected, the highest levels were released by the recycled material for all the legally regulated metals.

Regarding the results obtained by the diffusion leaching test, it can be concluded that similar diffusion curves were obtained regardless of the concrete type (HA-25 or HA-40) or the replacement percentage of natural aggregate.

The representation of diffusion curves helped identify the contaminant release mechanisms: while oxyanionic elements (as Mo and Cr) and Ba were released by diffusion mechanism and their curve was close to 1:0.5 slope, the more mobile species (as Zn and Cu) presented a flat line in the last stages of the test (due to the depletion of the soluble fraction).

The effect of the replacement percentage on the release of the monolithic samples of concrete was more marked in the HA-25 samples than in HA-40, due to the higher variations on the pH values registered in the first ones.

From the section of analysis about reaching the maximum leaching potential, it can be confirmed the different leaching behaviour of the more mobile metal cations (Zn and Cu) and the oxyanions (Cr and Mo). Thus, while the leaching threshold of the more mobile elements was far from their diffusion curves, the levels of Mo and Cr were very close to the threshold of maximum leachability.

Finally, the statistical results about the correlation between the leaching data and factors which could affect directly to the permeability of the concrete (density, porosity and absorption) showed a low $R^2$ coefficient in the most of cases. Only the more mobile species presented a higher correlation factor. It demonstrated that these physical factors are not as relevant to the release of metals as it was expected, which confirms the relevant role of chemistry on release of metals. It proves the difficult to reproduce the leaching phenomena and the complexity of analysing the complete processes that govern the pollutant release of the chemical species in study.

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# APORTACIÓN 2. ESTUDIO PRELIMINAR DE RESISTENCIAS EN MORTEROS Y HORMIGONES APLICANDO ESCORIAS DE BIOMASA COMO SUSTITUTO DE ÁRIDOS FINOS.

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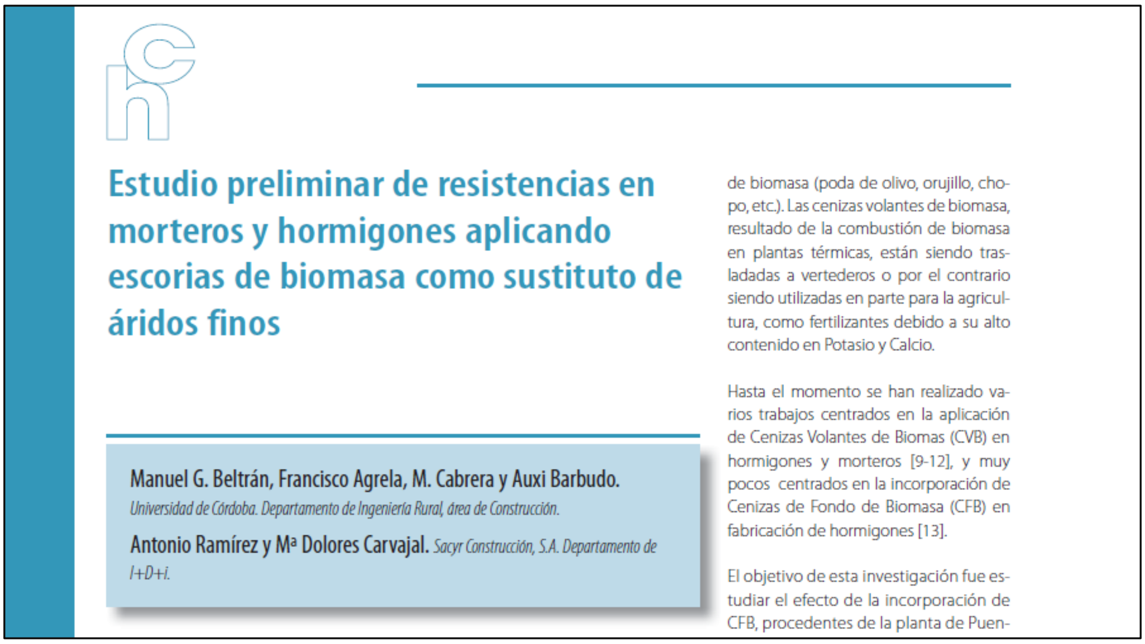

Estudio preliminar de resistencias en morteros y hormigones aplicando escorias de biomasa como sustituto de áridos finos

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de biomasa (poda de olivo, orujillo, chopo, etc.). Las cenizas volantes de biomasa, resultado de la combustión de biomasa en plantas térmicas, están siendo trasladadas a vertederos o por el contrario siendo utilizadas en parte para la agricultura, como fertilizantes debido a su alto contenido en Potasio y Calcio.

Hasta el momento se han realizado varios trabajos centrados en la aplicación de Cenizas Volantes de Biomas (CVB) en hormigones y morteros [9-12], y muy pocos centrados en la incorporación de Cenizas de Fondo de Biomasa (CFB) en fabricación de hormigones [13].

El objetivo de esta investigación fue estudiar el efecto de la incorporación de CFB, procedentes de la planta de Puen-

## *Resumen*

En búsqueda de la sostenibilidad medioambiental, es cada vez más común la explotación de energías renovables. España es un país con gran producción de biomasa procedente de los procesos productivos en la industria agrícola, y consecuentemente, la producción de energía a partir de combustión de biomasa es una alternativa viable que está en auge en estos últimos años. Sin embargo, la mayoría de los residuos generados a partir de la combustión de la biomasa son comúnmente depositados en vertederos, disminuyendo la vida útil de éstos y aumentando el coste de producción total del proceso.

Es por ello que resulta interesante la posibilidad de dar una salida económica y medioambiental a este tipo de residuos. Este trabajo pretende estudiar la viabilidad de la utilización de las escorias producidas en esta combustión en el ámbito de la construcción.

Para ello, se analizó el efecto de la incorporación de estas escorias en la fabricación de morteros y su influencia en la resistencia a flexión y compresión, así como las propiedades mecánicas y de durabilidad en hormigones no estructurales fabricados con éstas. Los resultados obtenidos desvelaron que las escorias de biomasa pueden utilizarse como árido fino para fabricar hormigones no estructurales de baja resistencia.

## *Abstract*

The production of electricity from renewable sources is becoming more usual. So, plant residues, call biomass, are applied actually in thermal plants to produce power. Spain is a country with high production of biomass from the agricultural industry, such as remnants of olive and other crops, and consequently, the production of energy from combustion of biomass is a viable alternative that is booming in recent years.

Two residues are mainly obtained from biomass burning process: fly ashes, and bottom ashes. The first ones are usually used as agricultural fertilizer due to

its high content of nutrients. However, the bottom ashes are often deposited in landfills due to its low chemical quality, decreasing the lifetime of these and increasing the total cost of production. For this reason, the possibility of an economic and environmental solution to this type of waste such as ash line biomass is such interesting.

This paper aims to study the feasibility of bottom ashes produced in plants where olive wastes are burned in order to apply them mainly in the field of construction of road infrastructure.

To this, the cementing potential capacity of the bottom ashes has been analyzed, producing mortars where natural sand is replaced by these recycled materials, and studying their influence in flexural and compressive strength.

To do this, a sample of bottom ash from the biomass combustion plant placed in Puente Genil (Córdoba, Spain) was characterized. Secondly, concretes were fabricated to study the effect of this ashes on the physical-mechanical properties such as compressive strength, flexural strength, density and absorption, and rate of ultrasonic pulses as well as studying properties of durability, as the penetration water under pressure, chloride penetration and retraction.

The obtained results revealed that concrete made with biomass bottom ash can be used in works of smaller physically demanding, as non-structural concrete, as long as a certain indications of placing are complied.

## *Introducción*

El estudio y utilización de áridos reciclados procedentes de residuos de construcción y demolición u otros orígenes está en auge debido a un gran crecimiento en la concienciación medioambiental y a las nuevas políticas medioambientales.

Investigaciones como las realizadas *Etxeberría et al. (2006)*[1] o Mas et al. *(2012)*[2] estudiaron la influencia de áridos reciclados de hormigón o mixtos respectivamente en su fracción gruesa.

Otras investigaciones, se centraron en la incorporación áridos reciclados en su fracción fina para sustituir arenas naturales [3,4] o en la mejora de hormigones con áridos reciclados mediante la incorporación de adiciones al cemento [5] o mediante la utilización de distintos tipos de cemento [6], o de super-plastificantes [7,8].

Sin embargo, investigaciones realizadas recientemente han abarcado el estudio de otro tipo de residuos, como son los procedentes de la combustión de diferentes tipos de biomasa (poda de olivo, orujillo, chopo, etc.). Las cenizas volantes de biomasa, resultado de la combustión de biomasa en plantas térmicas, están siendo trasladadas a vertederos o por el contrario siendo utilizadas en parte para la agricultura, como fertilizantes debido a su alto contenido en Potasio y Calcio.

Hasta el momento se han realizado varios trabajos centrados en la aplicación de Cenizas Volantes de Biomasa (CVB) en hormigones y morteros [9-12], y muy pocos centrados en la incorporación de Cenizas de Fondo de Biomasa (CFB) en fabricación de hormigones [13].

El objetivo de esta investigación fue estudiar el efecto de la incorporación de CFB, procedentes de la planta de Puente Genil de la empresa SACYR INDUSTRIAL, en morteros para determinar su carácter puzolánico, y estudiar las propiedades mecánicas y de durabilidad de hormigones no estructurales fabricados con ellas. Para ello, se fabricaron morteros y hormigones aplicándoles diversas tasas de sustitución de arena AN por CFB.

Este trabajo se ha realizado bajo dentro del proyecto "Estudio de propiedades de áridos reciclado, RAP y CFB y RCD, aplicación en infraestructuras lineales", proyecto realizado entre la empresa Sacyr Construcción y el Área de Construcción de la Universidad de Córdoba, y financiado por el Ministerio de Ciencia e Innovación y la Unión Europea a través del "Programa Operativo de I+D+i por y para el beneficio de las empresas (Fondo Tecnológico)" y el Fondo Europeo de Desarrollo Regional (FEDER), dentro el programa INNPACTO 2011, con una duración de 3 años.

## *Materiales*

### *Cemento*

Tanto para la fabricación de morteros como para la fabricación de hormigones se utilizó Cemento Portland, con una resistencia característica de 52,5MPa N/SR, sulfo-resistente y de alta resistencia inicial. En la Tabla 1 se muestran sus propiedades químicas.

**Tabla 1.** Propiedades del cemento

| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $K_2O$ | $Na_2O$ | SE. Blaine | Pérdida al fuego | Densidad |
|---|---|---|---|---|---|---|---|---|---|---|
| % | % | % | % | % | % | % | % | $cm^2/g$ | % | $(Kg/dm^3)$ |
| 20.18 | 4.14 | 4.51 | 63.75 | 0.91 | 3.24 | 0.75 | 0.31 | 3701 | 1.44 | 3.15 |

### *Áridos naturales*

Se han utilizado tres tipos de áridos naturales: una grava (G1), una gravilla (G2) y una arena (AN), todas de naturaleza granítica y procedentes de la planta áridos Gallardo, en la región de "La Serena" (Badajoz). En la Figura 1y Tabla 2 se exponen, respectivamente, las granulometrías y propiedades físicas de los áridos naturales.

*Cenizas de fondo de biomasa*

Se han utilizado CFB procedentes de la planta térmica ubicada en Puente Genil (Córdoba) en sustitución de AN, tanto en la fabricación de morteros como de hormigones. Para asemejar la granulometría de la CFB a esta arena, la fracción superior a 4 mm fue eliminada. En la Figura 1 y en la Tabla 2 se observan la granulometría y las propiedades analizadas respectivamente.

*Aditivo super-plastificante*

Con el objetivo de conseguir la consistencia deseada y mejorar tanto la relación agua/cemento como las resistencias de los morteros y hormigones, se utiilizó un aditivo súper-plastificante de la marca Rheobuild 1222 de BASF en diferentes porcentajes respecto de la cantidad de cemento.

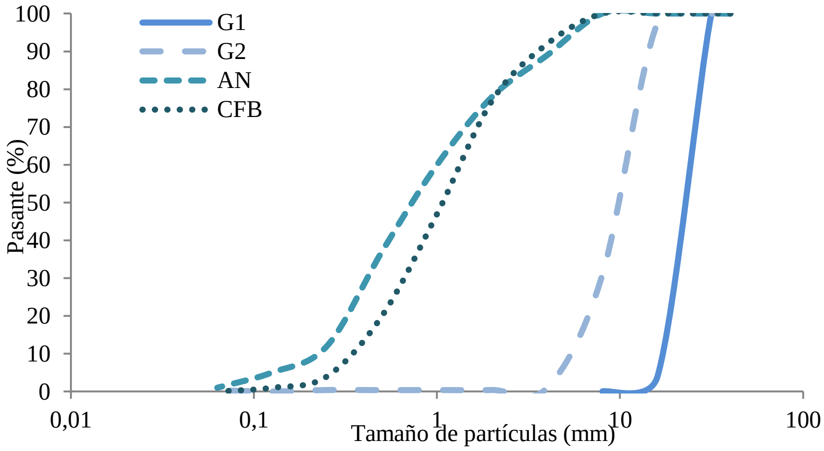


**Figura 1.** Análisis granulométrico

**Tabla 2.** Propiedades físicas de los áridos

| | | G1 | G2 | AN | CFB |
|---|---|---|---|---|---|
| Fracción (mm) | EN 933-1 | 16-31,5 | 4-16 | 0-4 | 0-4 |
| Densidad (Kg/dm$^3$) | EN1097-6 | 2,63 | 2,68 | 2,5 | 1,7 |
| Absorción (%) | | 0,80 | 1,53 | 1,3 | 19,9 |
| Los Ángeles (%) | EN1097-2 | - | 20 | - | - |
| Friabilidad (%) | EN83-115 | - | - | 12 | 38 |

En cuanto a la densidad, se observa que CFB mostró un valor significativamente inferior a los áridos naturales, y una absorción muy superior a la obtenida para el AN, por lo cual ha sido de gran importancia adicionar agua de saturación en proporción a la cantidad de CFB. El coeficiente de friabilidad de las CFB fue mucho más alto que el de AN. Todos los áridos naturales ofrecieron granulometrías continuas, como se observa en la Figura 1 permitiendo una distribución uniforme de partículas. A su vez, las CFB mostraron también una granulometría continua, similar a la AN.

## *Morteros fabricados con CFB*

La primera parte de este trabajó consistió en la fabricación de morteros para estudiar la capacidad cementante de las CFB aplicando sustituciones de AN por CFB.

### *Fabricación de amasadas y dosificaciones*

Se fabricaron tres amasadas y se rellenaron probetas prismáticas de dimensiones 40x40x160 mm de acuerdo con la Norma UNE-EN 196-1, aplicando en cada una unos porcentajes de sustitución en peso de AN por CFB del 0%, 5% y 10%. Las dosificaciones empleadas se muestran en la Tabla 3.

Se introdujeron los materiales en la mezcladora para su homogenizado y posteriormente se procedió a la determinación de la consistencia en una mesa de sacudidas. Para conseguir una correcta relación agua/cemento, se añadió al agua de amasado la cantidad de agua de saturación necesaria para las CFB, proporcional a la cantidad de CFB añadida.

Posteriormente, se colocó cada molde en la mesa de agitación para conseguir una correcta distribución del mortero. Tras la fabricación de éste, se introdujeron en una cámara con 100% de humedad durante 24 horas antes de su desmoldado y posteriormente, las de edad de rotura superior a 24 horas, se sumergieron en tanque de curado hasta la edad de rotura.

**Tabla 3.** Dosificaciones empleadas para morteros (gramos)

| | CEM | G1 | G2 | AN | CFB | AGUA | TOTAL | ADIT.(% CEM) |
|---|---|---|---|---|---|---|---|---|
| M-0CFB | 450 | 0 | 0 | 1350 | 0 | | 225 | 0,00 |
| M-5CFB | 450 | 0 | 0 | 1215 | 67,5 | | 239 | 0,45 |
| M-10CFB | 450 | 0 | 0 | 1080 | 135 | | 253 | 0,90 |

***Métodos experimentales.***

Tras la fabricación y curado de las probetas prismáticas en tanque de curado, se determinó la ***resistencia a flexión y compresión*** a diferentes edades (1, 2, 3, 7, y 28 días) de acuerdo con la norma UNE-EN 196-1.

***Resultados y discusión.***

Se determinó la ***consistencia*** de todos los morteros mediante la mesa de sacudidas. Las tres amasadas fabricadas obtuvieron un diámetro en torno a 200 mm, debido a que se realizaron amasadas de prueba aplicando diferentes cantidades de aditivo para conseguir una trabajabilidad similar.

**Tabla 4.** Resistencia a flexión y compresión para morteros (MPa)

| | FLEXIÓN | | | COMPRESIÓN | | |
|---|---|---|---|---|---|---|
| EDAD | M-0CFB | M-5CFB | M-10CFB | M-0CFB | M-5CFB | M-10CFB |
| 1 | 5,5 | 6,7 | 4,7 | 22,4 | 22,0 | 14,9 |
| 2 | 7,6 | 7,9 | 6,2 | 31,8 | 32,8 | 22,4 |
| 3 | 7,8 | 8,1 | 7,5 | 36,2 | 33,7 | 29,1 |
| 7 | 9,1 | 8,6 | 8,3 | 46,6 | 39,0 | 31,6 |
| 28 | 12,0 | 10,4 | 9,1 | 58,5 | 46,5 | 35,9 |

Se exponen en la Tabla 4 y en las Figuras 2-3 los resultados y evolución de resistencias a flexión y compresión obtenidas. En todas las amasadas se consiguió la consistencia solicitada de 200 mm.

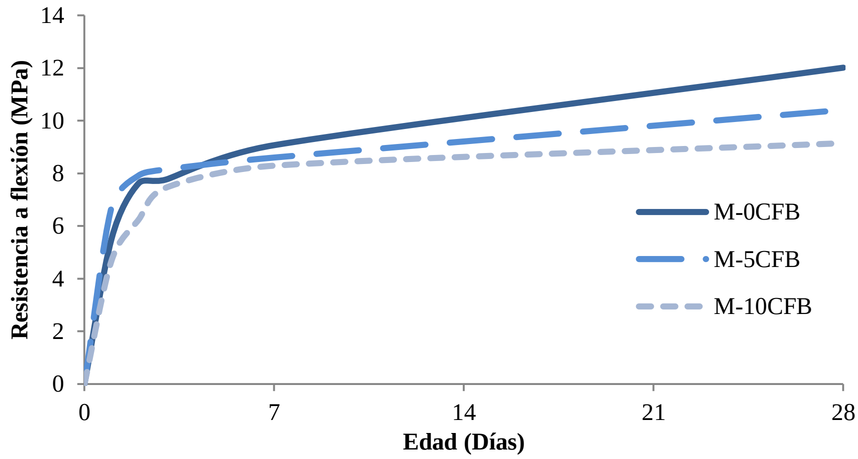


**Figura 2.** Evolución de resistencias a flexión para morteros.

Se observa en la Figura 2 una evolución de resistencias a flexión similar para las tres amasadas hasta la edad de 7 días. Sin embargo, a 28 días de edad, M-0CFB obtuvo una resistencia significativamente superior a los morteros fabricados con incorporación de CFB. Las resistencias a compresión, observadas en la Figura 3 mostraron evidentes diferencias desde los primeros días de curado, siendo dicha resistencia menor cuanto mayor es la tasa de sustitución.

En la Figura 4 se observan las resistencias a flexión y compresión relativas respecto del mortero de referencia (M-0CFB). A la edad de 28 días, la pérdida de resistencia a flexión fue en torno al 15% y 25% para M-5CFB y M-10CFB respectivamente. La pérdida de resistencia a compresión fue más significativa a 28 días de edad, siendo las pérdidas de resistencia de 20% y 39% para M-5CFB y M-10CFB respectivamente.

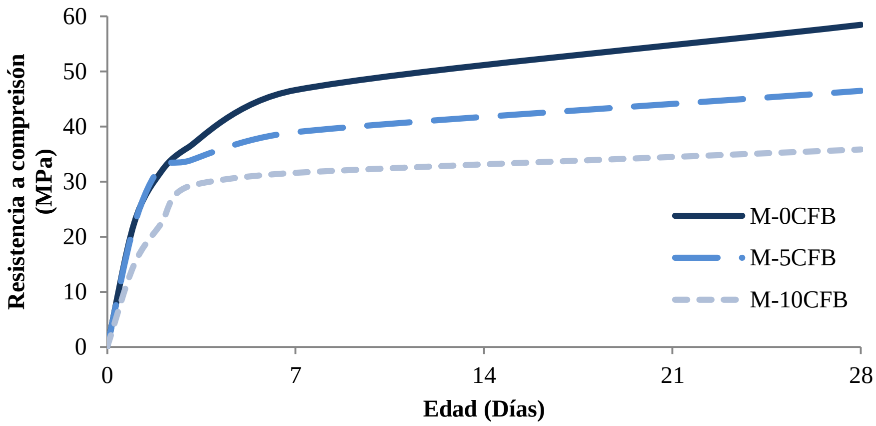


**Figura 3.** Evolución de resistencias a compresión para morteros

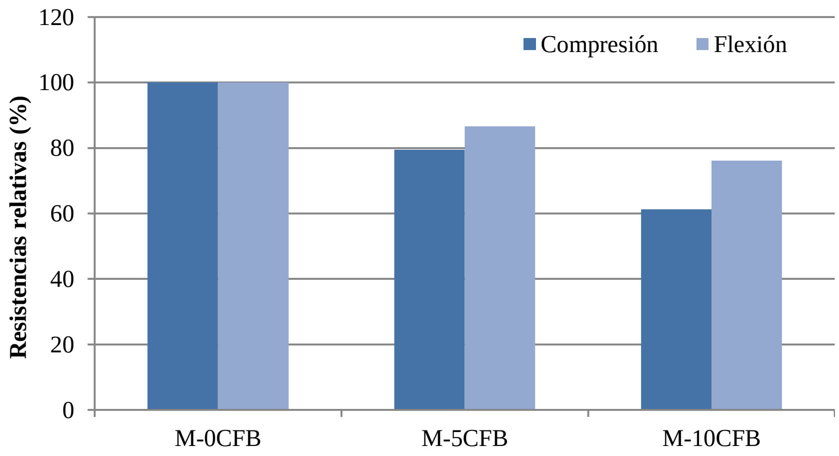


**Figura 4.** Resistencia a compresión y flexión a 28 días relativa para morteros con CFB respecto al mortero de referencia (M-0CFB)

## *Hormigones fabricados con CFB*

La segunda fase de la investigación se realizó con el fin de estudiar las propiedades mecánicas y de durabilidad en hormigones fabricados con sustituciones de 10% y 20% de AN por CFB.

### *Fabricación y dosificaciones*

Para la fabricación de hormigones, se realizaron 3 amasadas aplicando, de igual modo que para morteros, tres porcentajes de sustitución de AN por CFB distintos (0%, 10%, y 20%). La relación agua/cemento, la cantidad de cemento y la consistencia fueron constantes para las tres amasadas. Para mantener la relación agua/cemento efectiva, se añadió al agua de amasado el agua de saturación correspondiente a la absorción de CFB. Se utilizó el método de Bolomey para el cálculo de dosificaciones, las cuales se exponen en la Tabla 5. Se rellenaron probetas cúbicas de dimensiones 100 x 100 x 100 mm para resistencia a compresión y con probetas prismáticas de 10 x 10 x 40 $cm^3$.

En primer lugar, se introdujeron los áridos gruesos seguidos de los áridos finos y la cantidad de agua correspondiente al agua de saturación durante 50 minutos A continuación, sin parar la amasadora, se añadió el cemento y el agua de amasado con el aditivo disuelto previamente durante otros 5 minutos. Una vez realizada la amasada, se comprobó su consistencia mediante el cono de Abrams y se procedió al llenado y vibrado en mesa de vibrado de los moldes. Transcurridas 24 horas, se depositaron los moldes en una cámara de curado en condiciones de humedad y temperatura constante (100% y 20ºC).

**Tabla 5.** Dosificaciones empleadas para hormigones

| | CEM | GN | GRN | AN | CFB | AGUA TOTAL | PESO TOTAL | ADIT (% CEM) |
|---|---|---|---|---|---|---|---|---|
| H-0CFB | 275 | 462 | 696 | 810 | 0 | 165 | 2409 | 1 |
| H-10CFB | 275 | 462 | 696 | 729 | 81 | 165 | 2376 | 1,5 |
| H-20CFB | 275 | 462 | 696 | 648 | 162 | 165 | 2351 | 2 |

***Métodos experimentales***

Para el estudio de los hormigones, se han analizado diversas propiedades tanto físico-mecánicas como de durabilidad, cuya normativa aplicada se expone en la Tabla 6.

**Tabla 6.** Propiedades físico-mecánicas y de durabilidad

| Propiedades físico-mecánicas | | Propiedades de durabilidad | |
|---|---|---|---|
| Resistencia a compresión | UNE-EN 12390-3 | Pen. agua bajo presión | UNE-EN 12390-8 |
| Resistencia a flexión | UNE-EN EN 12390-5 | Pen. de cloruros | Basada en Otsuki et al. (1992) |
| Densidad del hormigón | UNE-EN 12390-7 | Retrac. del hormigón | ASTM C157 |
| Vel. Imp. ultrasónicos | UNE-EN 12504-4 | | |
| Consistencia | EN-12350-2 | | |

## *Resultados y discusión*

Tras la fabricación y curado de los hormigones fabricados, se analizaron las propiedades físico-mecánicas y de durabilidad, quedando los valores expuestos en las Tablas 7 y 8 respectivamente.

**Tabla 7.** Propiedades físico-mecánicas de los hormigones fabricados

| | Edad | H-0CFB | H-10CFB | H-20CFB |
|---|---|---|---|---|
| | 1 | 16.1 | 14.2 | 12.4 |
| Compresión (MPa) | 7 | 39.2 | 31.0 | 25.2 |
| | 28 | 47.1 | 36.1 | 31.4 |
| Flexión (Mpa) | 28 | 5.0 | 4.3 | 4.1 |
| Densidad (Kg/dm$^3$) | 28 | 2.39 | 2.34 | 2.28 |
| Absorción (%) | 28 | 6.77 | 7.03 | 7.34 |
| Ultrasonidos (Km/s) | 28 | 4.5 | 4.3 | 4.2 |

**Table 8.** Propiedades de durabilidad de los hormigones fabricados

| | Edad | H-0CFB | H-10CFB | H-20CFB |
|---|---|---|---|---|
| Penetración de agua (mm) | 28 | 41,6 | 68,5 | 73,7 |
| Penetración de cloruros (mm) | 28 | 19,1 | 24,2 | 30,6 |
| | 56 | 23,6 | 26,6 | 32,5 |
| | 28 | 232 | 376 | 480 |
| Retracción (µm/m) | 90 | 275 | 405 | 504 |
| | 180 | 302 | 422 | 527 |

*Consistencia del hormigón fresco*

La ***consistencia*** del hormigón fresco se determinó mediante el cono de Abrams según Norma EN-12350-2. Como era de esperar al igual que ocurrió en la fabricación de los morteros, la consistencia obtenida fue la esperada, tras los ajustes previos realizados variando las cantidades de aditivo. La consistencia obtenida fue plástica (8-9 cm).

*Resistencia a compresión*

La ***resistencia a compresión*** se determinó a 1, 7 y 28 días de edad en probetas cúbicas de 100 mm de lado. Se observa en la Figura 5 que a la edad de 7 días los tres hormigones fabricados ya habían alcanzado aproximadamente el 80% de su resistencia máxima a 28 días de edad.

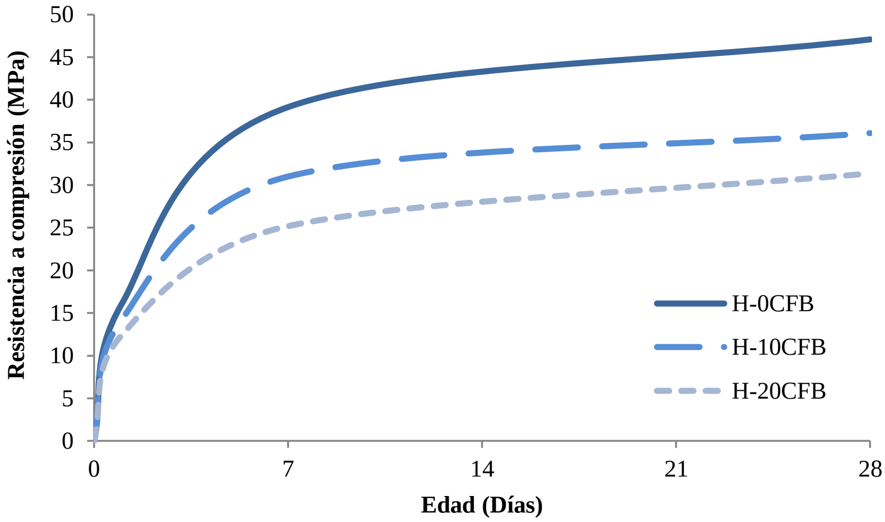


**Figura 5.** Evolución de resistencia a compresión para hormigones.

Por otro lado, se observa que H-0CFB obtuvo resistencias a compresión significativamente más altas que el resto de amasadas para todas las edades, siendo evidente a 7 días de edad.

En la Figura 6 se observa una pérdida de resistencia a compresión del 24% y 33% para sustituciones de AN por CFB del 10% y 20% respectivamente.

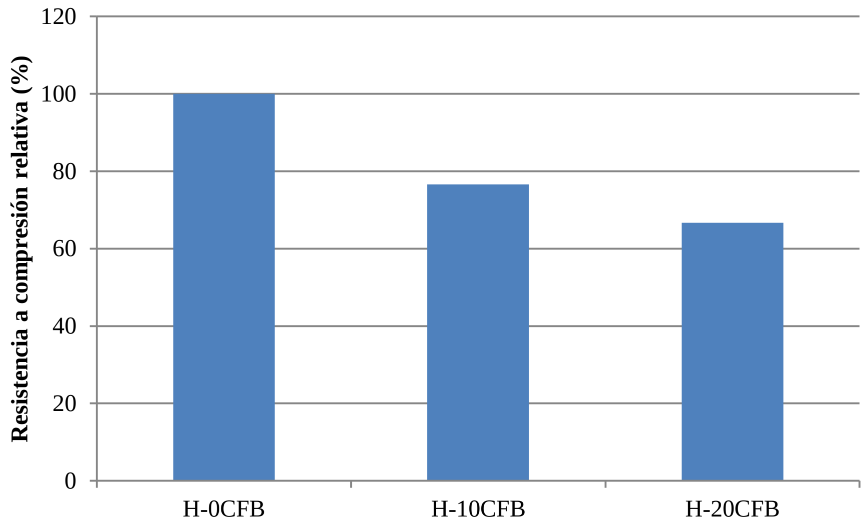


**Figura 6.** Comparativa del valor de resistencia a compresión a 28 días del hormigón con CFB respecto del hormigón de referencia (H-0CFB)

*Resistencia a flexión*

La ***resistencia a flexión*** se determinó a 28 días de edad de acuerdo a la norma UNE-EN EN 12390-5, utilizando probetas prismáticas de 100x100x400 mm.

El valor de flexión más alto corresponde al H-0CFB, descendiendo a medida que aumenta la tasa de sustitución de AN por CFB. (Tabla 7).

Sin embargo, se observa en la Figura 7 que, a pesar de la caída de resistencia a flexión, las pérdidas obtenidas con la incorporación de CFB fueron menos significativas respecto a las obtenidas para la resistencia a compresión, siendo de 15% y 19% para H-10CFB y H-20CFB respectivamente.

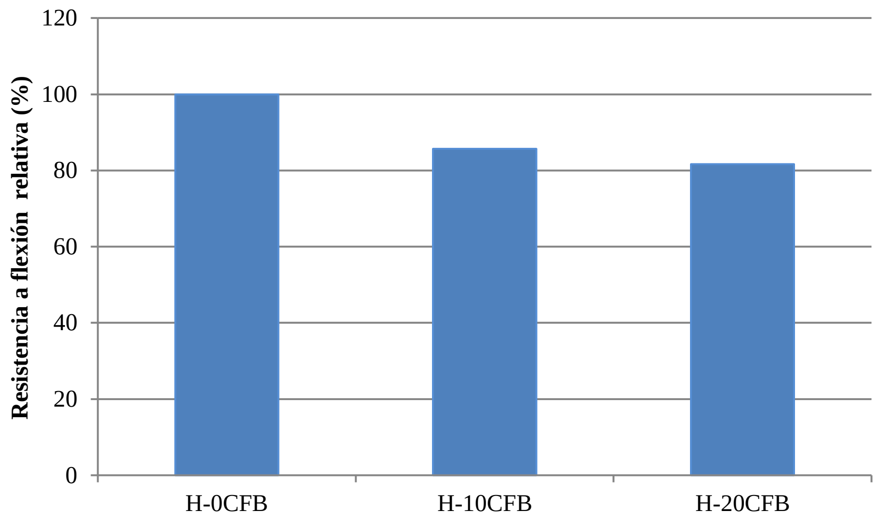


**Figura 7.** Comparativa del valor de resistencia a flexión a 28 días del hormigón con CFB respecto al hormigón de referencia (H-0CFB)

*Densidad del hormigón endurecido*

Los valores de ***densidad y absorción del hormigón endurecido*** se determinaron según la Norma UNE-EN 12390-7 para probetas cúbicas de 15 mm de lado a 28 días de edad. Los resultados se presentan en la Tabla 7.

La densidad del hormigón endurecido se redujo conforme aumenta la tasa de sustitución de AN por CFB, como cabía esperar, debido a la menor densidad de CFB respecto de AN.

En la Figura 8 se observan caídas de densidad de 2% y 4,5 % para sustituciones de 10% y 20% respectivamente.

Igualmente, como queda reflejado en la Figura 8, la absorción se vio afectada por la incorporación de CFB, siendo la caída con respecto al hormigón de referencia de 3,8% y 8,4% para tasas de sustitución de AN por CFB de 10% y 20% respectivamente.

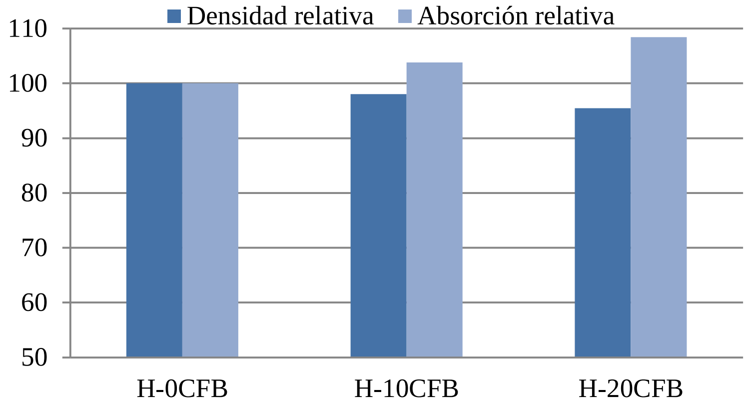


**Figura 8.** Comparativa de la densidad y absorción a 28 días de edad de los hormigones con CFB respecto del hormigón de referencia (H-0CFB)

*Velocidad de impulsos ultrasónicos*

La ***velocidad de impulsos ultrasónicos*** se obtuvo sobre probetas cúbicas de 15 mm de lado conforme a la norma UNE-EN 12504-4 a 1, 7 y 28 días de edad, presentando en la Tabla 7 los datos recogidos a 28 días de edad. En la Figura 9 se observa un aumento significativo de la velocidad de ultrasonidos hasta los 7 días de edad para los tres hormigones analizados, siendo los valores obtenidos cercanos a los obtenidos a 28 días de edad.

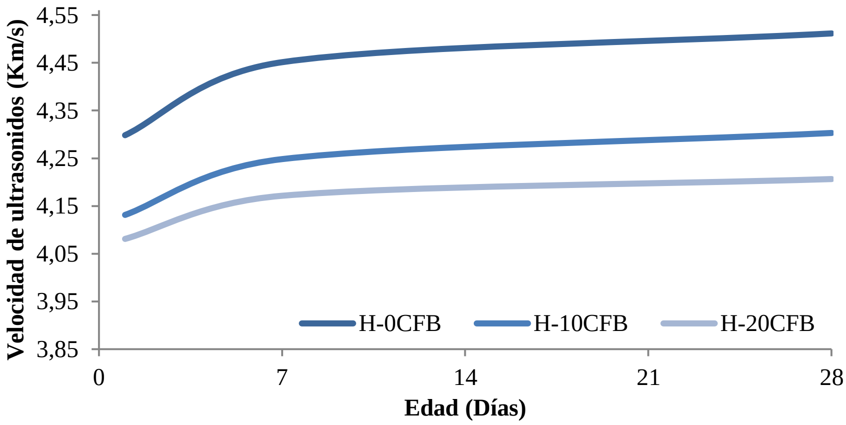


**Figura 9.** Evolución de la velocidad de impulsos ultrasónicos.

A 28 días de edad, la velocidad de ultrasonidos fue significativamente menor conforme aumentó la tasa de sustitución de AN por CFB (Figura 10), siendo las pérdidas de velocidad de ultrasonidos de 4,7% y 6,7% para tasas de sustitución de 10% y 20 % respectivamente.

Por otro lado, la evolución de la velocidad de ultrasonidos mantuvo una buena correlación con la resistencia a compresión a 28 días de edad, tal como se observa en la Figura 11, pudiéndose estimar la resistencia a compresión a partir de la velocidad de ultrasonidos y viceversa con cierto grado de fiabilidad para este caso concreto.

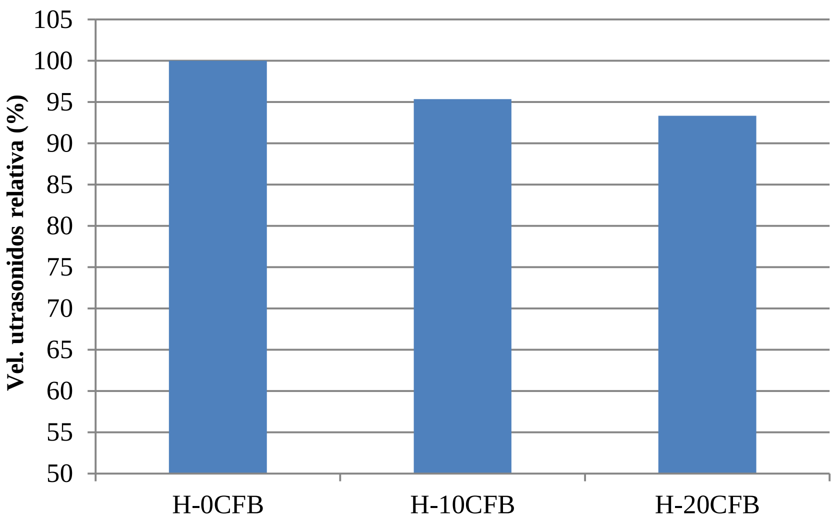


**Figura 10.** Comparativa de velocidad de ultrasonidos respecto del hormigón de referencia (H-0CFB)

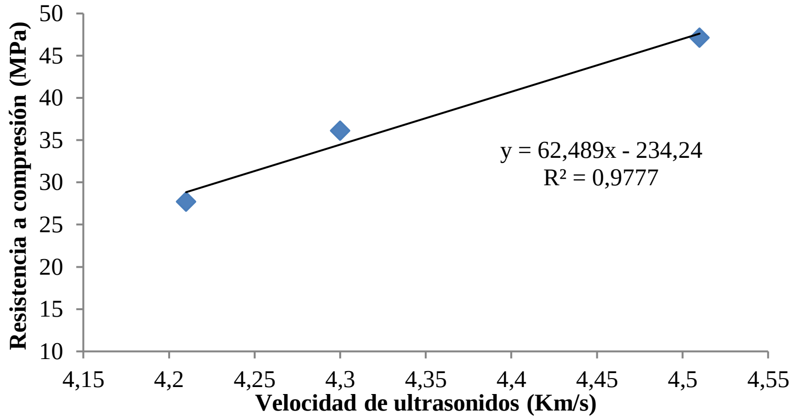


**Figura 11.** Relación entre la Resistencia a compresión y la velocidad de ultrasonidos a 28 días de edad.

*Penetración de agua bajo presión*

El ensayo de ***penetración de agua bajo presión (PABP)*** se determinó a 28 días de edad sobre probetas cilíndricas de 150 mm de diámetro y 300 mm de altura a una presión de 5 Atm, siguiendo la norma UNE-EN 12390-8 (Tabla 8). La penetración de agua aumentó con la incorporación de CFB, siendo dichos aumentos del 64,6% y 77% para incorporaciones del 10% y 20% de CFB respectivamente (Figura 12).

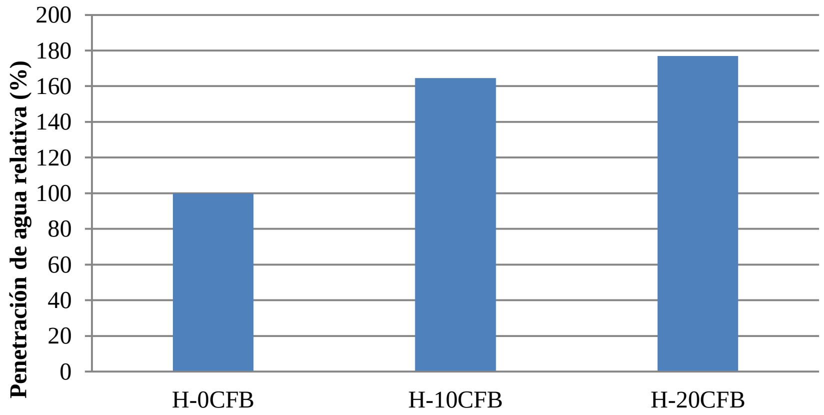


**Figura 12.** Penetración de agua respecto del control (H-0CFB )

*Penetración de cloruros*

Para la realización del ensayo de ***penetración de cloruros***, se sumergieron probetas prismáticas de 100 mm de diámetro y 200 mm de altura en una disolución de NaCl con una concentración de 20.000 ppm por litro. Para la determinación de la penetración del ión cloruro se impermeabilizó con una resina epoxi específica su sección lateral, dejando las bases del cilindro expuestas a la solución.

A las edades de 28 y 56 días de exposición, se dividieron las probetas en dos secciones mediante el ensayo de tracción indirecta y se aplicó una solución de $AgNO_3$. Esta solución en contacto con la solución de NaCl provoca una coloración violácea en la zona necesaria para su posterior medición (Tabla 8).

Tal como se observa en la Figura 13, la penetración de cloruros aumentó con el incremento de la tasa de sustitución de AN por CFB. El aumento a la edad de 28 días para H-10CFB y H-20CFB fue de 26,4% y 60,3% respectivamente. En cambio, a la edad de 56 días, el aumento relativo de la penetración de cloruros fue menor, siendo para H-10CFB y H-20CFB de 12,7 % y 37,7% respectivamente.

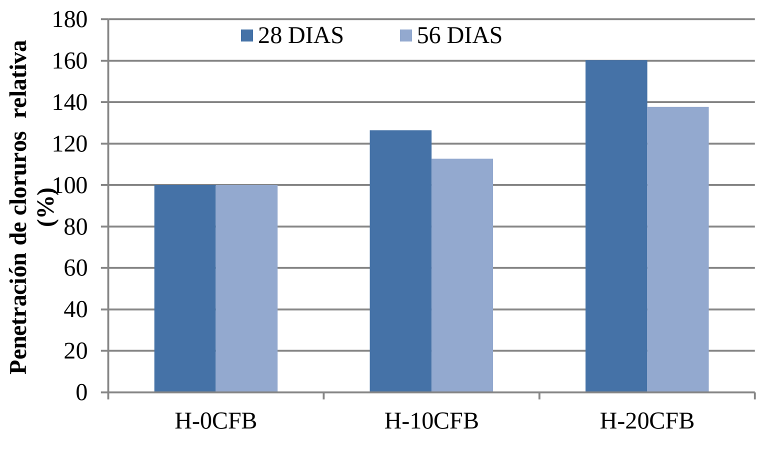


**Figura 13.** Penetración de cloruros respecto del control

En la Figura 14 se observa la relación existente entre la penetración de agua bajo presión y la penetración de cloruros, siendo posible estimar la penetración de agua a partir de la penetración de cloruros y viceversa.

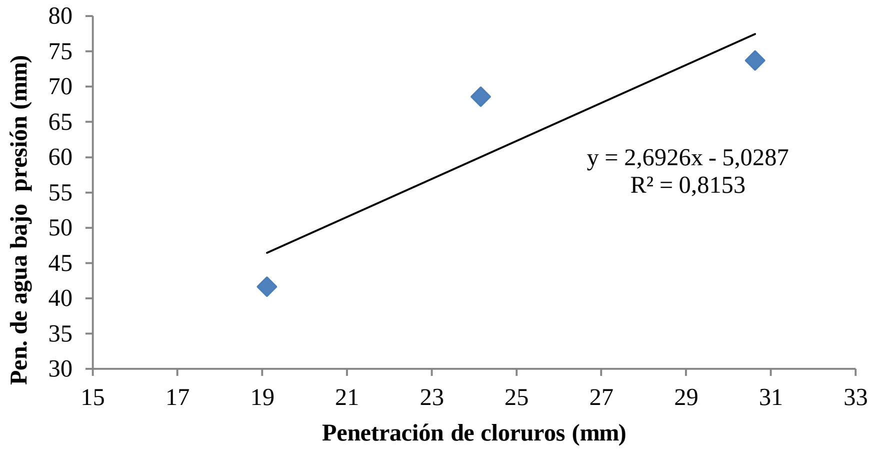


**Figura 14.** Relación entre la penetración de agua bajo y presión y la penetración de cloruros a 28 días de edad.

*Retracción del hormigón*

La ***retracción*** del hormigón se determinó en probetas prismáticas de 100 x 100 x 500 mm a 1, 7, 28, 90 y 180 días de edad en base a la norma ASTM C157. Las probetas analizadas fueron introducidas el día 1 de medición en una cámara de retracción bajo unas condiciones de humedad y temperatura constantes (50% y 20ºC). Los valores obtenidos quedan definidos en la Tabla 8 y Figura 15.

Se observa en la Figura 15 que, desde una temprana edad, la retracción experimentada por los hormigones con CFB fue mayor que la del hormigón de control. Hasta la edad de 28 días la retracción aumenta considerablemente para los tres hormigones. Sin embargo, a partir de dicha fecha, la retracción se estabiliza y aumenta más levemente.

En cuanto a la comparativa entre hormigones, en la Figura 16 se observa que, a 28 días de edad, la retracción experimentada por los hormigones con CFB fue de 50,4% y 81,4% para sustituciones de 10% y 20% respectivamente.

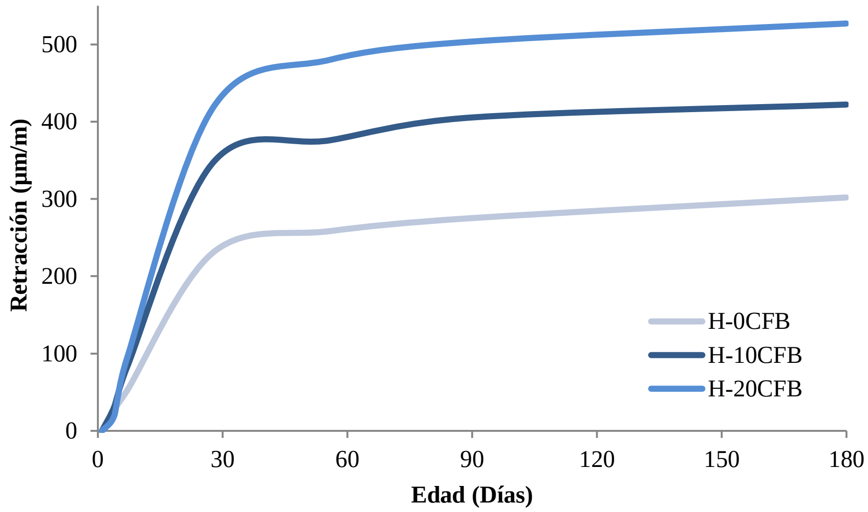


**Figura 16.** Retracción del hormigón

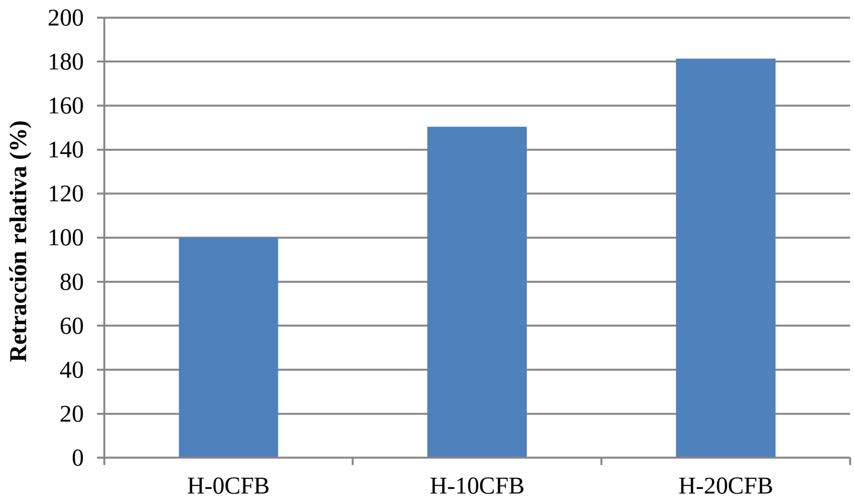


**Figura 17.** Comparativa de la retracción respecto del hormigón de referencia (H-0CFB)

## *Conclusiones*

Tras el análisis de los resultados obtenidos, se pueden extraer las siguientes conclusiones:

-La sustitución de AN por CFB ha repercutido negativamente en la resistencia a compresión y flexión a los morteros fabricados para las tasas de sustitución realizadas, por lo que se concluye que la CFB no aporta capacidad cementante.

-La sustitución de AN por CFB ha aportado valores de resistencia a compresión y flexión significativamente bajos respecto al hormigón sin CFB, por lo que la adición de CFB no ha aportado mejoras en la resistencia flexión y compresión. A su vez, la densidad fue menor con el incremento de CFB y la absorción mayor, por lo que la incorporación de CFB ha desmejorado las propiedades mecánicas de los hormigones fabricados.

-La penetración de agua bajo presión, penetración de cloruros y retracción, han sido más elevadas en los hormigones con CFB respecto del hormigón control, por lo cual, CFB ha repercutido negativamente en las propiedades de durabilidad.

Como conclusión final se puede afirmar que la incorporación de CFB en morteros y hormigones empeora la resistencia a flexión y compresión, descartando propiedades de puzolanicidad, con lo cual se recomienda el uso de CFB para hormigones no estructurales con bajas tasas de sustitución.

## Agradecimientos

El presente trabajo forma del proyecto "ESTUDIO DE PROPIEDADES DE ARIDOS RECICLADO, RAP Y EB RCD, APLICACIÓN EN INFRAESTRUCTURAS LINEALES", financiado por el Ministerio de Ciencia e Innovación dentro del Plan Nacional de Investigación Científica, Desarrollo e Innovación Tecnológica, 2008-2011 y cofinanciado por el Fondo Europeo de Desarrollo Regional (FEDER) dentro el programa INNPACTO 2011.

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# APORTACIÓN 3. INFLUENCE OF ORGANIC MATTER CONTENT ON THE MECHANICAL PROPERTIES OF MORTAR MANUFACTURED WITH BIOMASS BOTTOM ASHES

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**Influence of organic matter content in the mechanical properties of mortars manufactured with Biomass Bottom Ashes.**

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**1. Introduction** – The generation of energy from biomass combustion has increased significantly in recent years. The use of such materials involves the generation of waste which is landfilled. In order to provide an environmental solution to this type of waste, some studies have been conducted to investigate their mechanical behaviours in mortars and concretes [1-4].
In Spain, there are a large number of biomass power plants, which primarily use olive residues. These plants produce electrical power and two types of residues are obtained: Biomass Fly Ashes (BFA), used

## *Introduction*

The generation of energy from biomass combustion is increasing significantly in recent years. In Spain, there are a large number of biomass power plants, which primarily use olive residues. These plants produce electrical power and two types of residues are obtained: biomass fly ash (BFA), which is used as agricultural fertiliser, and biomass bottom ash (BBA), which is transported to landfills or dumps because their mechanical behaviour in civil applications is not well known.

However, some researches about BBA were performed: Cabrera et al. (2014) studied the physical properties of the BBA and use on roads. Rodriguez et al (2014) studied the chemical properties of the BBA. Cuenca et al. (2013) studied the behaviour of self-compacting BFA in concrete. Furthermore, Maschio (2011) studied the behaviour of mortars containing BFA. Depending on the combustion process and raw materials used, BBA could contain a high percentage of unburned particles and organic matter.

This factor considerably detrimental the physical and chemical properties of the material, which may result in not being able to be used. Therefore, this study aims to determine the amount of organic matter of six samples from three power generation plants and its effect on the compressive strength of mortars.

## *Materials*

Six types of Biomass Bottom Ash (BBA) from three biomass power plants (P1, P2 and P3) were characterized physically (Table 1) and chemically (Table 2) to determine their nature and their amount of organic matter.

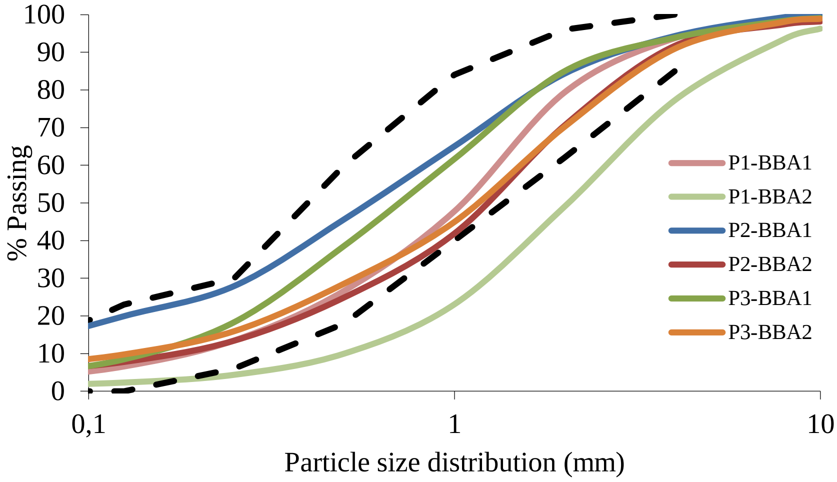


**Figure 1.** Particle size distribution

It is observed in Figure 1 that all samples exhibited a good particles size distribution, ensuring continuity in all fractions. However, only one sample was left out of the limits established in the Concrete Spanish Instruction (EHE-08 ) for fine fraction.

On the other hand, it is observed in Table 1 a low dry density and a high absorption for all samples tested, such being significantly higher absorption in the P2 samples. Similarly, it is observed that the samples with the highest content of light particles corresponded to samples of PG. Lower values of light particles corresponded to samples L.

**Table 1.** Physical properties of BBA

| Property | Unit | Standard | P1-BBA1 | P1-BBA2 | P2-BBA1 | P2-BBA2 | P3-BBA1 | P3-BBA2 |
|---|---|---|---|---|---|---|---|---|
| Ap. Density ($\rho_a$) | ($kg/dm^3$) | | 2.48 | 2.56 | 2.57 | 2.41 | 2.36 | 2.1 |
| Dry Density ($\rho_{rd}$) | ($kg/dm^3$) | UNE-EN 1097-6 | 1.74 | 1.69 | 1.24 | 1.15 | 1.23 | 1.33 |
| SSD Density ($\rho_{ssd}$) | ($kg/dm^3$) | | 2.04 | 2.03 | 1.76 | 1.67 | 1.71 | 1.7 |
| Absorption ($W_{24}$) | (%) | | 17.12 | 20.15 | 41.84 | 45.69 | 38.59 | 27.38 |
| Light particles | (%) | UNE EN-1744-1 | 47.79 | 29.56 | 85.79 | 65.22 | 55.01 | 42.86 |
| Friability test | (%) | UNE 83-115 | 18 | 19.6 | 23.2 | 25.4 | 25 | 17 |

**Table 2.** Chemical properties of BBA

| Property | Unit | P1-BBA1 | P1-BBA2 | P2-BBA1 | P2-BBA2 | P3-BBA1 | P3-BBA2 |
|---|---|---|---|---|---|---|---|
| Water-soluble sulphates | % $SO_3$ | 0.67 | 0.29 | 0.5 | 0.29 | 0.28 | 0.24 |
| Acid-soluble sulphates | % $SO_3$ | 0.76 | 0.47 | 0.6 | 0.5 | 0.51 | 0.51 |
| Sulphur | % $SO_3$ | 0.53 | 0.56 | 0.7 | 0.5 | 0.45 | 0.51 |
| Chlorides | % | 0.25 | 0.13 | 0.33 | 0.29 | 0.21 | 0.04 |
| Potential alkali-silica reactivity | | NR | NR | NR | NR | NR | NR |
| Potentia alkali-carbonate reactivity | CaO/MgO | 5.53 | 5.37 | 6.46 | 5.25 | 3.82 | 4.09 |
| | % $Al_2O_3$ | 2.01 | 2.53 | 2.27 | 2.22 | 2.73 | 2.11 |

## *Experimental tests*

After the characterization of 6 materials, the amount of organic matter was determined calcining the samples according to standard UNE-EN 1744-1.

Moreover, to determining the influence of organic matter according to the loss of compressive strength, 6 specimens were divided into two types: calcined and uncalcined, performing with those samples required mortars according to the UNE-EN 1744-1. The compressive strength was determined at 28 days of age.

## *Results and Discussion*

Table 3 shows the results obtained for the determination of organic matter and the compressive strength of the samples analyzed. As expected, the uncalcined BBA mortars have experienced strengths smaller than mortars with calcined BBA compression in all cases. P1-BBA1 and P1-BBA2 had lower compressive strength losses, followed by PG-BBA1 and PG-BBA2. Samples with higher strength loss were P3-BBA1 and P3-BBA2

The loss of compressive strength was closely related to the organic matter content, as shown in Table 3 and in Figure 2. Figure.2 shows the correlation between the organic matter and loss of compressive strength, being demonstrated in this case the importance of organic matter in the compressive strength of mortars.

**Table 3.** Compressive strength and organic matter content

| | Comp. Strength Calcined | Comp. Strength Not calcined | Strength loss (%) | Relative Com. Strength | Organic matter content (%) |
|---|---|---|---|---|---|
| **P1-BBA1** | 19.51 | 17.67 | 9.43 | 90.57 | 8.64 |
| **P1-BBA2** | 21.69 | 20.84 | 3.92 | 96.08 | 8.5 |
| **P2-BBA1** | 19.9 | 16.57 | 16.73 | 83.27 | 9.08 |
| **P2-BBA2** | 17.73 | 14.57 | 17.82 | 82.18 | 14.2 |
| **P3-BBA1** | 20.54 | 15.5 | 24.54 | 75.46 | 15.86 |
| **P3-BBA2** | 23.34 | 14.57 | 37.57 | 62.43 | 21.78 |

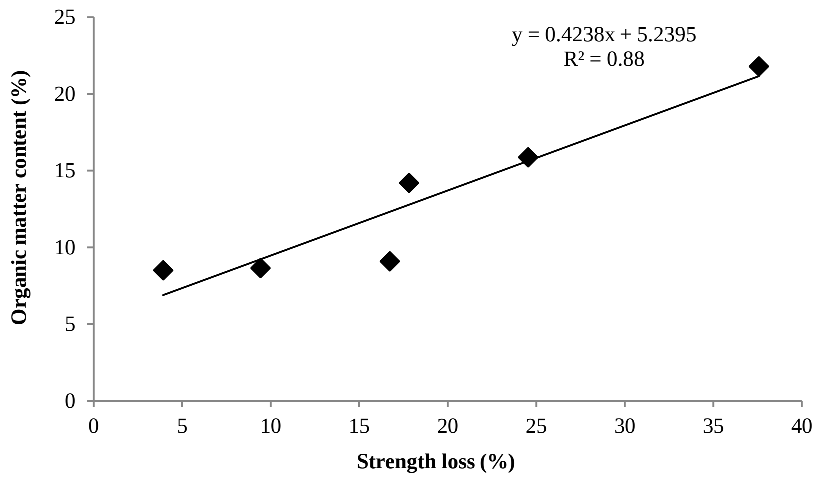


**Figure 2.** Correlation between strength loss and organic matter content

## Conclusions

A higher content of organic matter in the BBA is related to the loss of strength of mortar, so that the existence of organic matter negatively affects the mechanical properties of mortars.

It is recommended the elimination of organic matter by calcination process to improve the properties of the BBA for use in mortars.

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